TD-99-013

HGQ-04 Production Report

by

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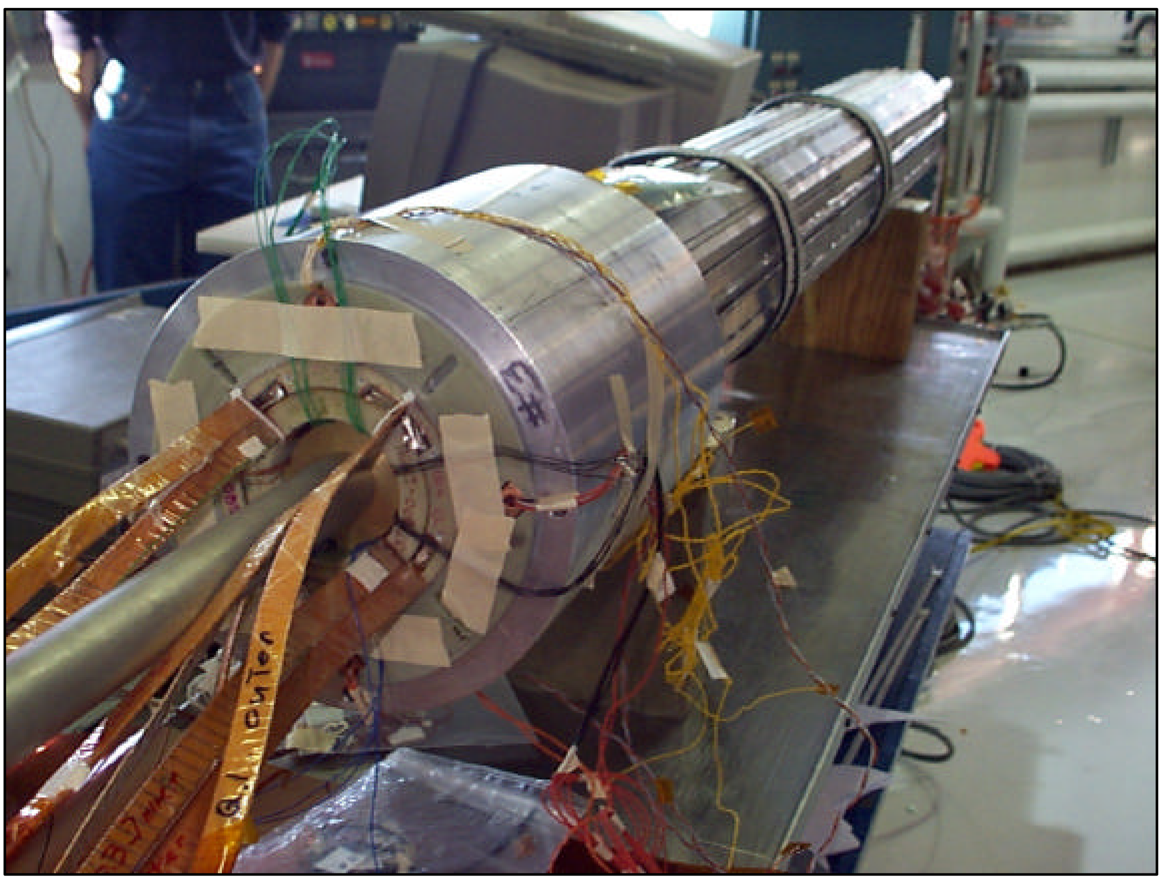
1.0 Introduction

This report summarizes the production stages of the fourth 2-meter long model magnet, HGQ-04. These model magnets are part of the US LHC program in which the FERMILAB has to fabricate and test 20 IR quadropoles for CERN. The baseline design is described in the HGQ Conceptual Design Handbook. HGQ-04 is the second magnet with an internal splice. It was meant to be similar to HGQ03, that is, internal splice coils cured at 190C with polyimide adhesive on the cable insulation and Ultem end parts.

Notable differences between HGQ03 and HGQ04 are that HGQ04 had a different reel of inner cable, with the same midthickness but slightly higher keystone angle, slightly larger inner coil curing cavity size, (.028in. vs. .020 in.), collet end clamps on both ends instead of full round collar laminations, and solid (welded) collar packs at both transition regions. HGQ04 was also to have the collets longitudinally attached to the end plates by bolts, although this feature was never implemented because HGQ04 production was aborted before the magnet was yoked. Other differences between HGQ03 and HGQ04 are shown in Table 1.

But during the fabrication of HGQ-04, HGQ-03 was tested and the quench performance did not show any significant improvement compared to the last two magnets. A second version of HGQ-03 was built to make some new improvements but still the results were not satisfying (TD-98-052 HGQ-03 Production Report). It was decided that it wouldn't be appropriate to put precious time and effort to build another magnet, which has similar characteristics to HGQ-03. The magnet production was stopped after the collared coil assembly stage.



HGQ-04 with lean end clamp installed

	HGQ-03	HGQ-03-1	HGQ-04
Inner Cable Strand No.	38	38	38
Inner Cable lay direction	Right Lay	Right Lay	Right Lay
Outer Cable Strand No.	46	46	46
Outer Cable lay direction	Left Lay	Left Lay	Left Lay
Cable Pre-baking	None	None	None
Inner Cable Insulation	25uM x 9.5mm w/ 54% overlap surrounded by 50uM x 9.5mm w/2mm gaps w/QI	25uM x 9.5mm w/ 54% overlap surrounded by 50uM x 9.5mm w/2mm gaps w/QI	25uM x 9.5mm w/ 55% overlap surrounded by 50uM x 9.5mm w/2mm gaps w/QI
Outer Cable Insulation	25uM x 9.5mm w/ 50% overlap surrounded by 50uM x 9.5mm butt lapped w/QI	25uM x 9.5mm w/ 50% overlap surrounded by 50uM x 9.5mm butt lapped w/QI	25uM x 9.5mm w/ 50% overlap surrounded by 50uM x 9.5mm butt lapped w/QI
Coil Curing temperature	190C	190C	190C
Inner Coil target size	+.015 in., +375uM	+.015 in., +375uM	+.015 in., +375uM
Inner Coil MOE	5.3GPa	5.3GPa	4.5GPa
Outer Coil target size	+.010 in., +250uM	+.010 in., +250uM	+.010 in., +250uM
Outer Coil MOE	10.5GPa	10.5GPa	10.5GPa
Target Prestress	83MPa	83MPa	83MPa
Coil end azimuthal Shim System	Outer and inner coil ends shimmed to be same as body, tapering off toward end of saddle.	Outer and inner coil ends shimmed to be same as body, tapering off toward end of saddle.	Shim ends to be same as body, tapering off toward end of saddle.
End Part Material	Ultem	Ultem	Ultem
End Part Configuration	Iteration #1, 4 block design. Wedges extended in outer coil.	Iteration #1, 4 block design. Wedges extended in outer coil.	Iteration #1, 4 block design. Wedges extended in outer coil. Saddles shortened by 21mm.
Splice Configuration	Internal	Internal	Internal
Voltage Tap Plan	MD-344883/MD-344884	MD-344883/MD-344884	
Inter layer strip heaters	Traditional, single element.	Traditional, single element.	Traditional, single element.
Outer layer strip heaters	McInturff design, double element	McInturff design, double element	SSC Design, single element
Key extension	Ultem	Ultem	Ultem
Inner coil Bearing Strips	Brass, full length except cut for strain gauges.	Brass, full length except cut for strain gauges.	Brass, full length except cut for strain gauges.
Outer coil Bearing Strips	Phosphor Bronze, full length except cut for strain gauges.	Phosphor Bronze, full length except cut for strain gauges.	Phosphor Bronze, full length except cut for strain gauges.
Collar configuration	Individual collars over entire body.	Individual collars over entire body.	Regular collars over body, except "solid" welded packs at each end.
Collar key configuration	3 inch long, "lined up' together longitudinally.	3 inch long, "lined up' together longitudinally.	3 inch long, "lined up' together longitudinally.

Strain Gauges	4 beam gauges on inner and outer coil, 4 capacitor gauges on inner and outer coil.	4 beam gauges on inner and outer coil, 4 capacitor gauges on inner and outer coil.	4 beam gauges on inner and outer coil, 4 capacitor gauges on inner and outer coil.
Spot Heaters	?	?	?
End Radial Support	Full Rounds on both ends.	Full Rounds on both ends, supported by yoke.	Collet end clamps on both ends.
Collar/Yoke Interface	Radial clearance between collar and yoke.	Radial interference between collar and yoke.	Radial clearance between collar and yoke.
Quadrant Lead Configuration	Single leads with solid copper piece as stabilizer.	Single leads with solid copper piece as stabilizer.	Double leads with copper only cable as stabilizer.
End longitudinal loading			N/A
Yoke Key Width	24m	23mm	N/A
Strain Gauges on Skin	Yes	Yes	N/A
End Plate Thickness	50mm	50mm	50mm
Coil Fabrication Start Date	2/1/98		5/8/98
Collared Coil Start Date	5/25/98		10/5/98
Yoke Assy Start Date	8/4/98	10/29/98	
Completion Date	8/19/98	11/24/98	1/19/99

Table 1: *Comparison between HGQ-03, HGQ-03-1 and HGQ-04*

2.0 Pre-Production R&D

The mechanical end lengths of the HGQ magnets required the ends of the magnet to be shortened. The intent was to reduce the length of the end-saddles, bullet preload plate and the end plate. But only the end saddles were shortened, by 21 mm. A series of tests were conducted to check the rigidity of the shortened end saddles. Compression tests were done on the shortened end saddles to ensure that the force applied by the bullets would not damage the saddles. Forces up to 6000 lbs. were applied to saddles pairs in a test fixture. The saddles were not damaged.

Good bonding between the end parts and the conductor was achieved by using QIX sheet adhesive between the end parts and the first few turns.

The inner coils in magnet HGQ03 were .005 in (125 uM) smaller azimuthally than the target size. The cable insulation system for HGQ04 was therefore modified to increase the cable insulation thickness, thereby increasing the coil size. The inner cable insulation system for HGQ04 was "one layer of .001 x .375 bare Kapton with 55% overlap (.040 land) surrounded by 1 layer of .002 x .375 kapton with 2mm gaps with QI polyimide adhesive". The first inner test coil (HGQi027) was still smaller than the desired goal. The curing cavity size was increased from +.020 in. to +.028 in. This increased the coil size slightly to about .003 in. smaller than the target of +.015 in. All inner HGQ04 coils were cured with this cavity size.

All HGQ04 outer coils were wound with the same insulation system as HGQ03 and cured with the same +.005 cavity size as HGQ03.

3.0 Superconducting Cable

3.1 Cable Parameters

The following table lists the main cable parameters:

PARAMETER	UNIT	INNER CABLE DESIGN	INNER CABLE FOR HGQ-04	OUTER CABLE DESIGN	OUTER CABLE FOR HGQ-04
Radial width, bare	mm	15.4 +/- 0.025	15.407	15.4 +/- 0.025	15.4050
Minor edge, bare	mm	1.325	1.312	1.055	1.051
Major edge, bare Midthickness, bare	mm mm	1.589 1.457 +/- 0.006	1.602 1.457	1.237 1.146 +/- .006	1.241 1.146
Keystone angle,	deg	0.90 +/- 0.1	1.077	0.68 +/- 0.1	0.703
Cable packing factor		0.91	0.91	0.91	
Number of strands		38	38	46	46
Strand diameter Pitch direction Pitch length	mm mm	0.808 right 114	 right 114	0.648 left 101.6	 left

Table 3: *Cable parameters as provided by LBNL.*

The cables were cleaned before insulation with Axarel 6100 in the SSC cleaning module.

3.2 Cable and Wedge Insulation

The following table summarizes the cable insulation parameters.

PARAMETER	INNER CABLE	OUTER CABLE
Number of wraps	2	2
Inner wrap: -material -adhesive -wrap structure -thickness *	 Kapton tape 25 μm × 9.5 mm None Spiral wrap with 55% overlap 56.9 μm	 Kapton tape 25 μm×9.5 mm None Spiral wrap with 48% overlap 48.8 μm
Outer wrap: -material -adhesive -wrap structure -thickness *	 Kapton tape 50 μm ×9.5 mm Polyimide ("QI") Spiral wrap with 2 mm gap 41.9 μm	 Kapton tape 50 μm × 9.5 mm Polyimide ("QI") Spiral wrap, .015 gaps "butt lapped" 49.5 μm

Table 4: *HGQ-04 cable insulation parameters.*

* "Thickness" refers to the integrated thickness of insulation on one side of one cable.

The wedges were insulated identical to their respective coils.

4.0 Coil Fabrication

There are typically 5 inner and outer cured coils made for each model magnet with the 8 most consistent coils used for the magnet assembly. HGQ-04 had a 6th inner coil made because the mold cavity was increased by 8 mils to 28 mils. The change in mold cavity increased the coil size by about 2 mils and lowered the modulus to 4.3 GPa.

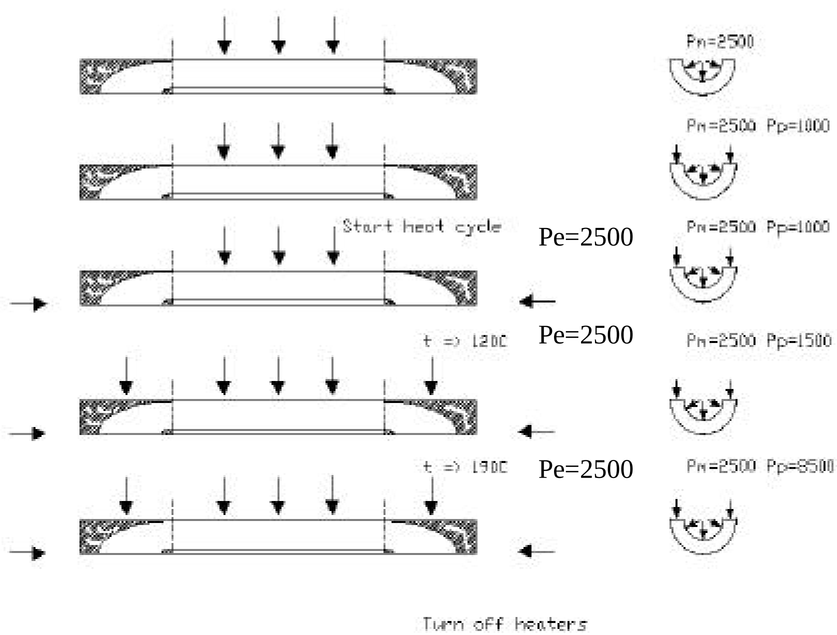
COIL NUMBERS	REEL NUMBER	COIL SIZE UM	COIL SIZE UM; MILS (AVERAGE)	MODULUS (GPA)	TARGET COIL SIZE
HGQi-027 [*, 1]	634		286; 11.26	5.21	15 mils
HGQi-028 [*, 2]	634		339; 13.30	4.67	
+HGQi-029	634	A:315 B:319	312; 12.28	4.05	
+HGQi-030	634	A:323 B:331	327; 12.87	4.12	
+HGQi-031	634	A:335 B:300	318; 12.52	4.93	
+HGQi-032 [4]	634	A:325 B:327	326; 12.83	4.17	
+HGQo-021	623	A:246 B:234	240; 9.44	8.06	10 mils
HGQo-022 [5]	623		240; 9.44	9.01	
HGQo-023 [3]	623		261; 10.28	9.36	
+HGQo-024	623	A:275 B:250	262; 10.33	9.37	
+HGQo-025	623	A:277 B:256	266; 10.49	8.85	
+HGQo-026 [4]	623	A:278 B:272	274; 10.78	9.10	

+ ⇒ Coils which will be used in magnet
* ⇒ Sized with old (hand system)
1 ⇒ Cured with +0.020 mil cavity size
2 ⇒ Double Cured
3 ⇒ Popped Strand at the preform
4 ⇒ 2 QIX sheet adhesive were used between end-parts and conductor; black adhesive was not used
5 ⇒ Turn to turn short at RE (probably between turn 2 and 3)

Table 5: Summary of the inner and outer coil fabrication history for HGQ-04

4.1 Winding and Curing

Six inner and five outer coils were wound, cured and measured for HGQ-04. The winding tension for these coils was 70 lbs., same as HGQ-03 coils. A QIX sheet adhesive was placed during winding between all the end-parts and the cable. The cavity sizes for the curing mold are +28 mils with respect to the nominal size for inner coils and + 5 mils for outer coils. The curing cycle is identical for both inner and outer coils. The temperature and pressure regimes are same as in HGQ-03. The loading scheme is shown below:



[taken from HGQ-02 production report]:
Fig. 1: *Curing Cycle for HGQ-04 coils.* P_m *= Mandrel pressure (PSI);* P_p *= Platen pressure (PSI);* P_e *= End pressure (PSI).*

4.2 Coil Body Size and Modulus

The coil azimuthal size and modulus measurements were taken at 8000 PSI to 14000 PSI. The design pressure for both during warm conditions is 12000 PSI or 83 MPa. Coils were measured with 3-inch gauge length along the straight section of the magnet, from LE to RE. The hand measuring system is updated with a computer based data acquisition measuring system just before the measurements of HGQ-04 coils began. There was a slight discrepancy at the readings between the old system and the new system. Especially the modulus values marked a big difference compared to HGQ-03 coils. But it is then found out that small changes in size make big difference on modulus value. The discrepancy is analyzed and studied and the measurements are tuned for the new automated measuring system.

Tables 6 and 7 list the coil numbers and the corresponding average coil size and modulus. The inner coil modulus is decreased slightly from 5 to 4 GPa due to slight size increase obtained by the curing cavity size increase for +8 mil.

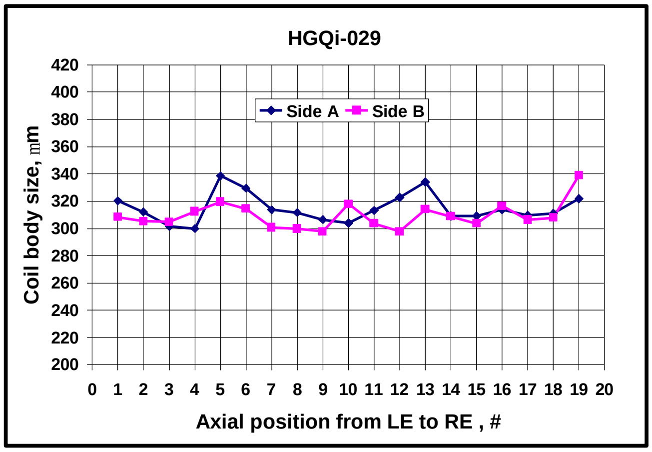
Coil #	Coil average modulus [GPa] at pressure range 55-97 MPa		Coil size at 83 MPa coil pressure [μm]			
	Average	Stand. Div.	Side A	Stand. Div.	Side B	Stand. Div.
HGQi-029	4.05	0.12	315	11	319	10
HGQi-030	4.12	0.11	323	8	331	16
HGQi-031	4.93	0.16	335	12	300	11
HGQi-032	5.17	0.11	325	12	327	17

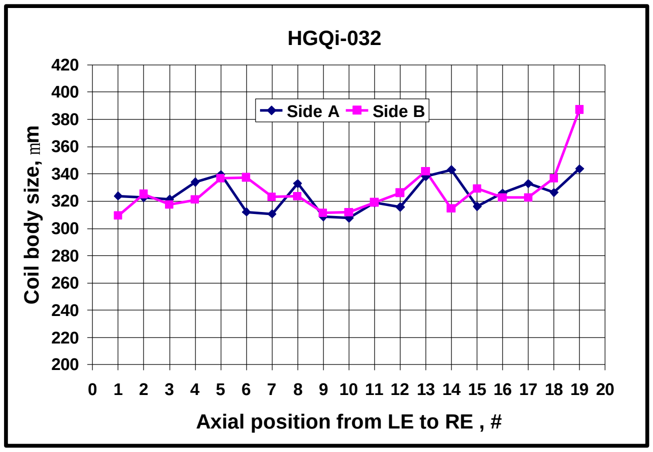
Table 6. *Inner Coil body size and Modulus.*

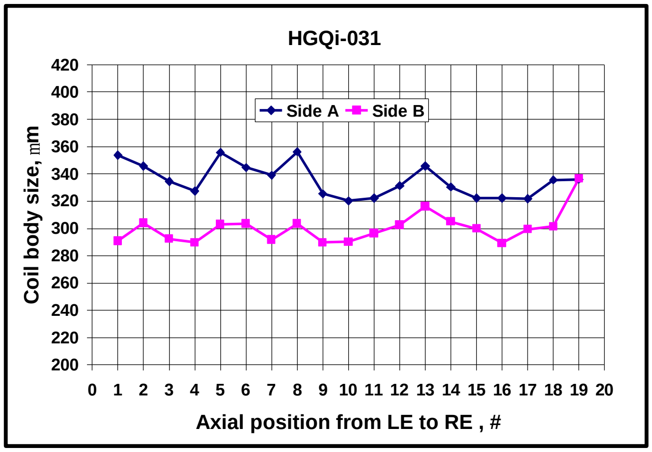
Coil #	Coil average modulus [GPa] at pressure range 55-97 MPa		Coil size at 83 MPa coil pressure [μm]			
	Average	Stand. Div.	Side A	Stand. Div.	Side B	Stand. Div.
HGQo-021	8.06	0.82	246	31	234	22
HGQo-024	9.37	0.48	275	23	250	26
HGQo-025	8.85	0.50	277	28	256	27
HGQo-026	9.10	0.57	278	32	272	29

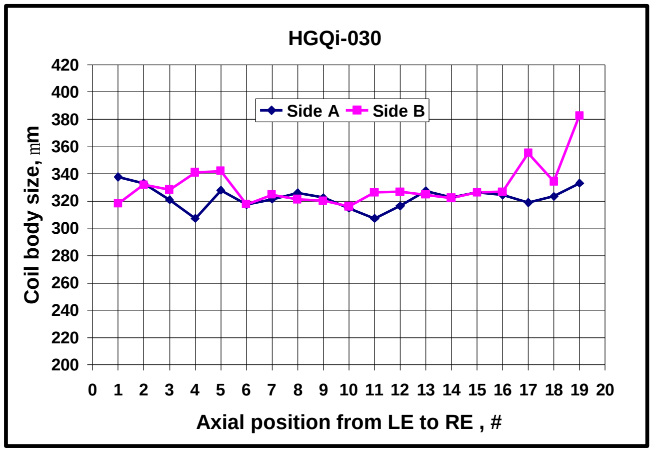
Table 7. *Outer Coil body size and Modulus.*

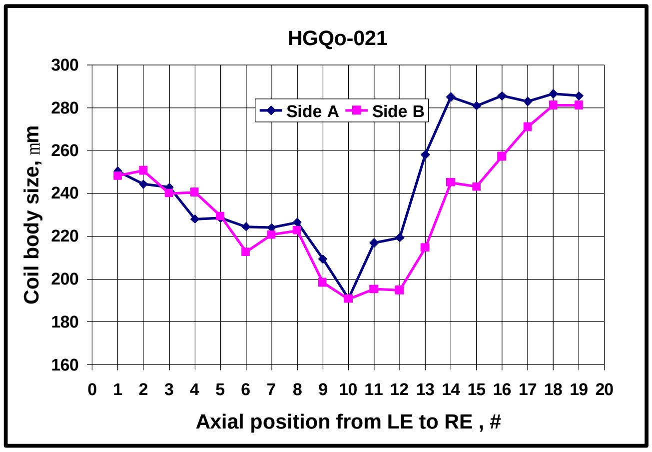
Variation of the coil size along the length of the coils is shown in Fig 2. Note that Side A is the winding side of the cable and the lead end of the cable is on Side B.

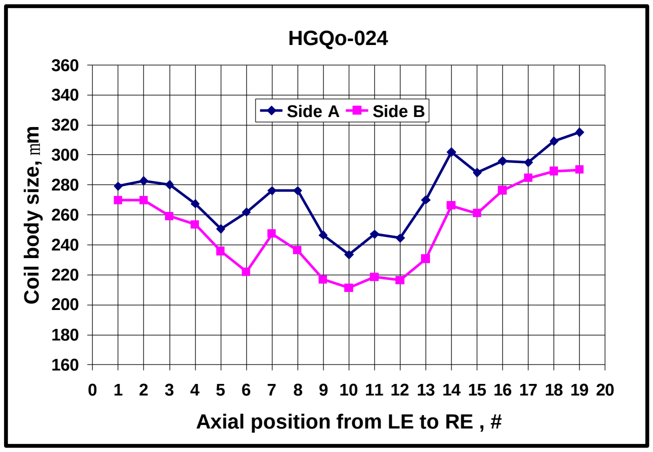

HGQi-029
Side A
Side B
Coil body size, mm
Axial position from LE to RE , #


HGQi-032
Side A
Side B
Coil body size, mm
Axial position from LE to RE , #


HGQi-031
Side A
Side B
Coil body size, mm
Axial position from LE to RE , #


HGQi-030
Side A
Side B
Coil body size, mm
Axial position from LE to RE , #


HGQo-021
Side A
Side B
Coil body size, mm
Axial position from LE to RE , #


HGQo-024
Side A
Side B
Coil body size, mm
Axial position from LE to RE , #

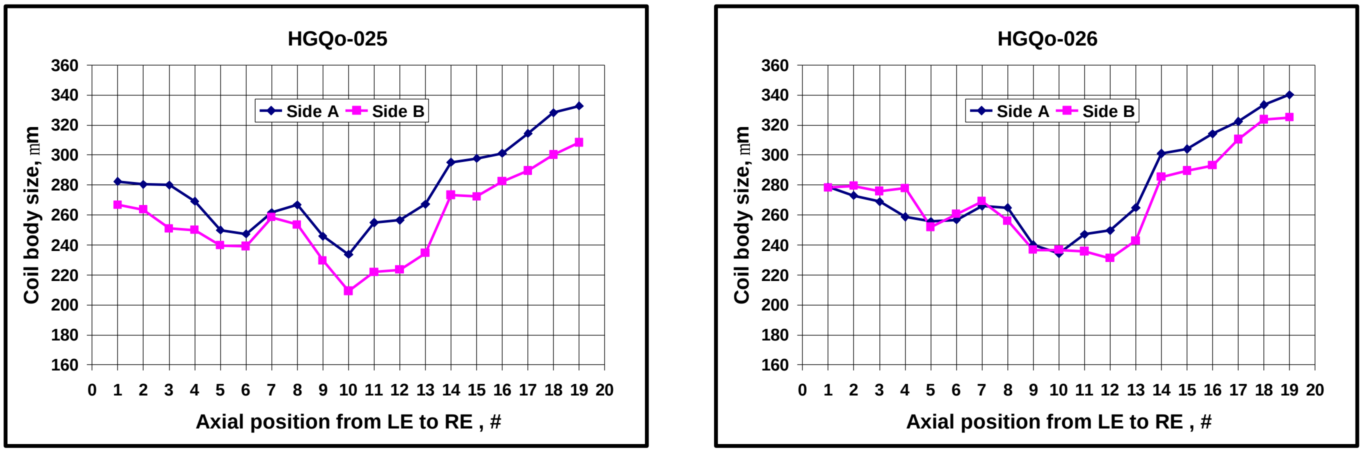


Fig. 2: *Variation of the coil size for both inner and outer coils along the length of the magnet.*

Outer coils size after measurement showed that +10 mil over the nominal size is achieved with the current insulation thickness and curing cavity. Inner coil size was still undersize by 3 mil. So an extra of 3 mil Kapton was added to the straight body section of the inner coils to bring their size to +15 mil over the nominal size.

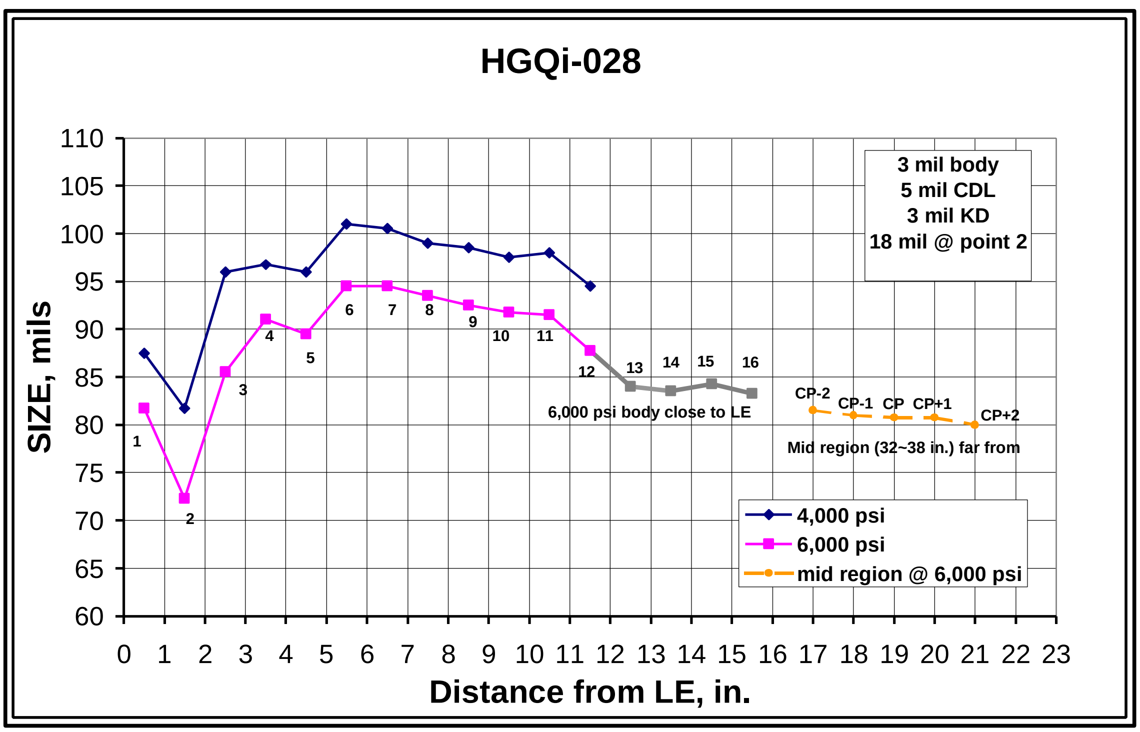
4.3 End-Load Experiments

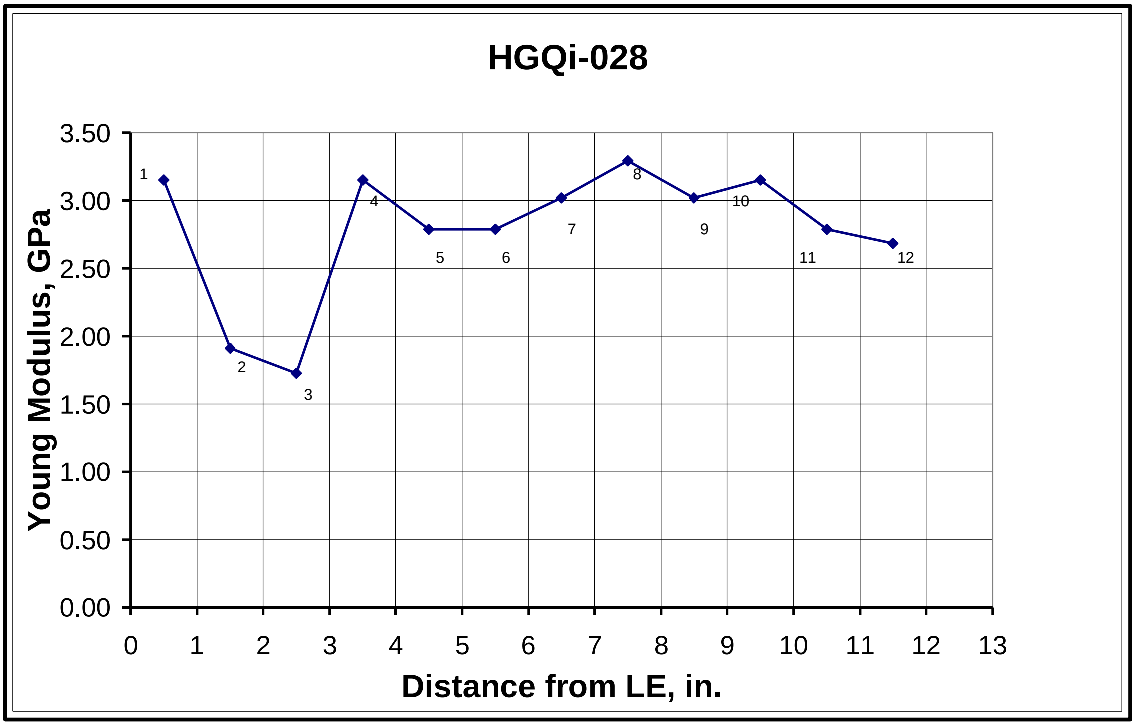
Azimuthal end compression tests are done on all the magnet coils using a 5 inch long block at 12000 coil PSI, to test for turn-to-turn shorts and measure end size. To get precise measurements of the end shape, finer increments of one inch were used on only one inner and one outer coil, respectively. The one-inch measurements are done only on one coil, since the test is somewhat destructive and may potentially damage the coil.
The one-inch increment tests were done at 4000 and 6000 coil PSI only, instead of the 12000-PSI tests done with the longer blocks, to minimize the chance for damage. Previous fine increment tests were done at 6000 and 12000 PSI on test coils, but the lower values were used for the HGQ04 coils because they are thought to be particularly susceptible to damage, for two reasons:

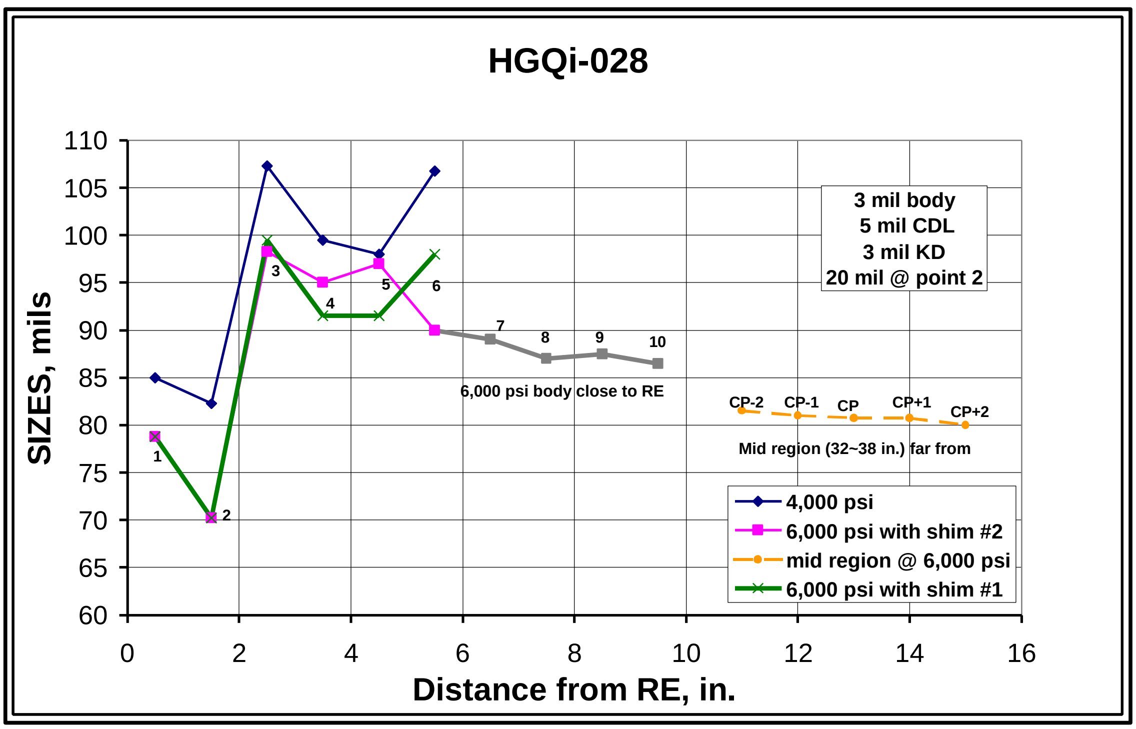
1.) The HGQ04 saddles were modified to make the end length shorter. As a result, a "half hole" appears at the end of the saddle, causing stress concentrations, which could lead to cracking.

2.) The batch of Ultem 2300 material used for HGQ04 saddles was tested to be slightly weaker than the previous batch used for HGQ02 and HGQ03.

Below are the results of the inner and outer coil LE and RE end compression test results:




HGQi-028
Young Modulus, GPa
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0 1 2 3 4 5 6 7 8 9 10 11 12 13
Distance from LE, in.
1 2 3 4 5 6 7 8 9 10 11 12


HGQi-028
SIZES, mils
110
105
100
95
90
85
80
75
70
65
60
0 2 4 6 8 10 12 14 16
Distance from RE, in.
3 mil body
5 mil CDL
3 mil KD
20 mil @ point 2
6,000 psi body close to RE
CP-2 CP-1 CP CP+1 CP+2
Mid region (32~38 in.) far from
4,000 psi
6,000 psi with shim #2
mid region @ 6,000 psi
6,000 psi with shim #1

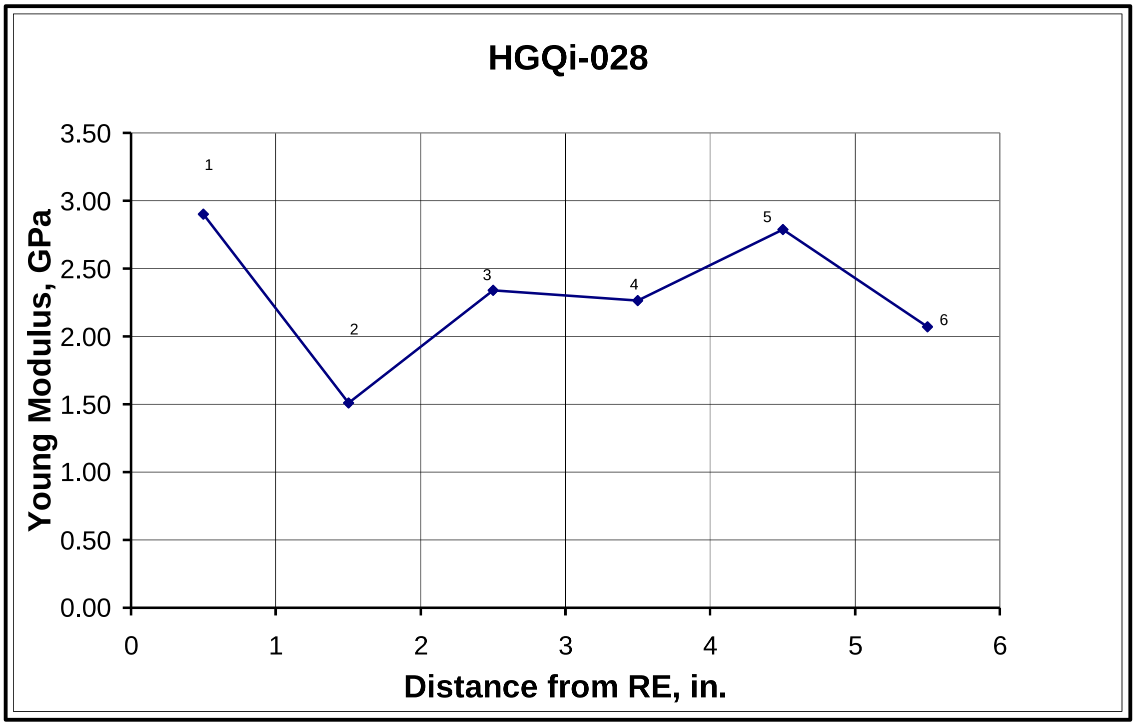
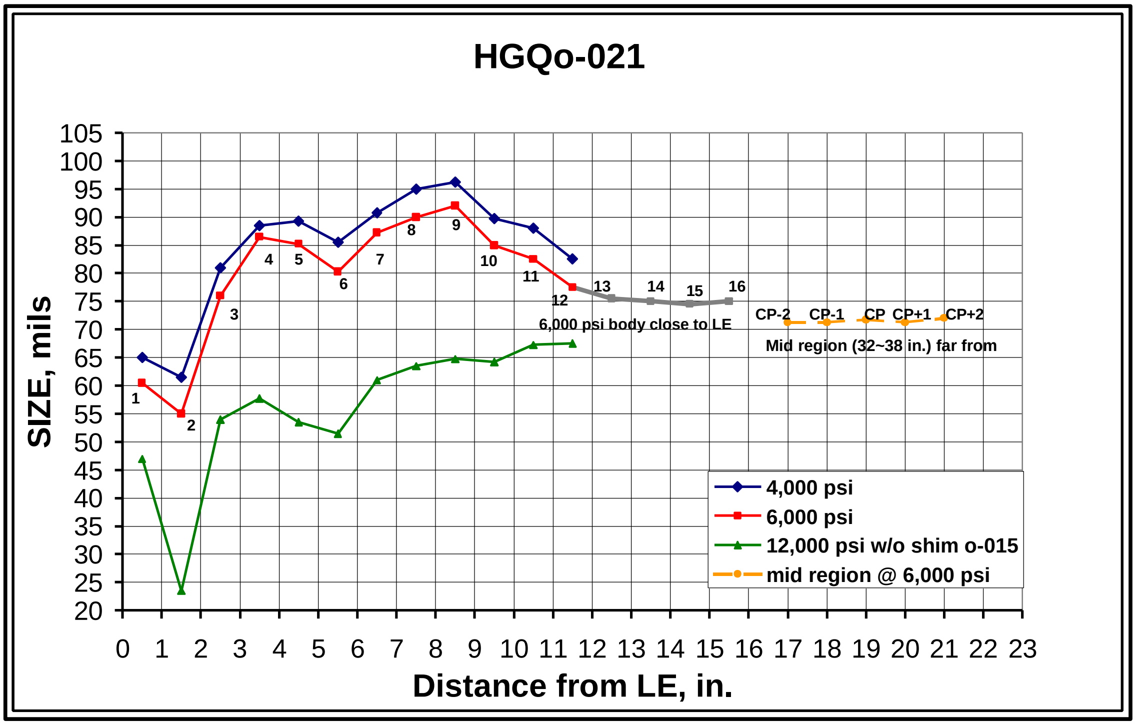
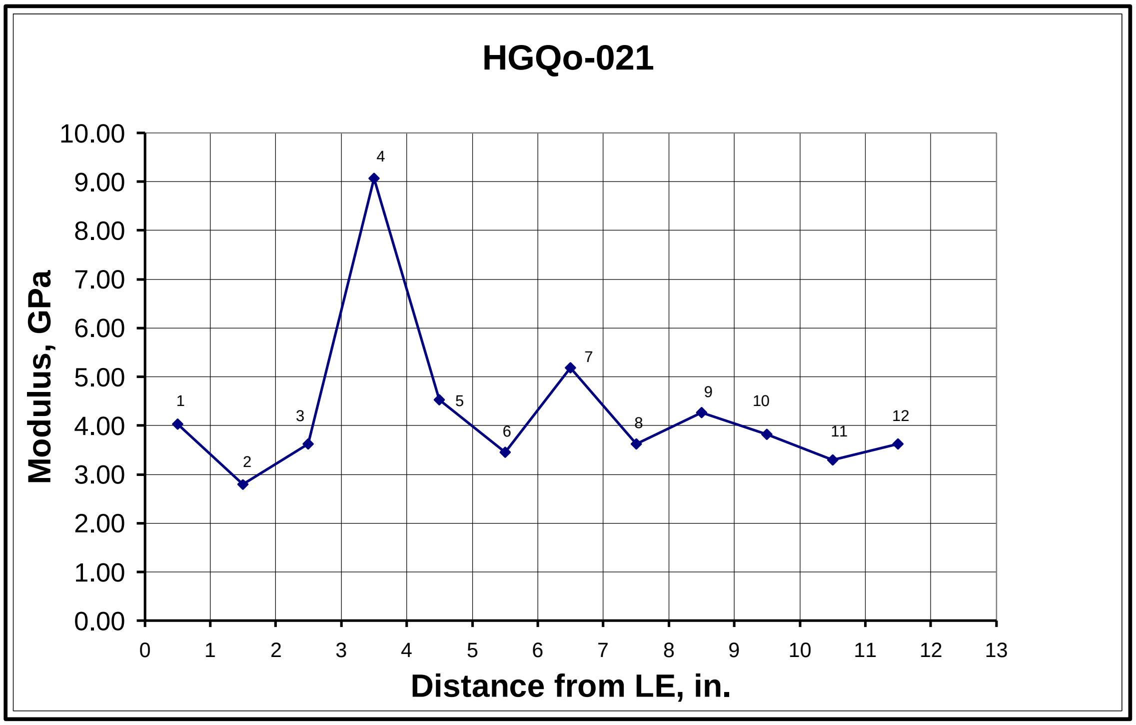
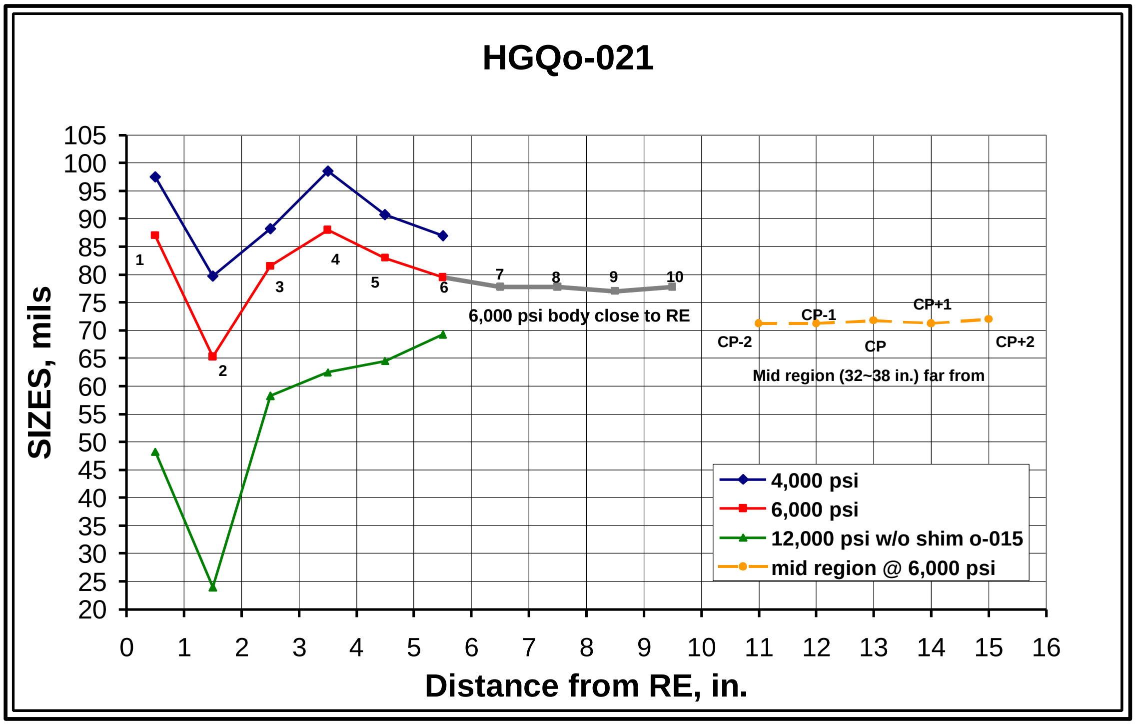


Fig. 3: Inner *Test Coil Size and Modulus*




HGQo-021
Modulus, GPa
10.00
9.00
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0
1
2
3
4
5
6
7
8
9
10
11
12
13
Distance from LE, in.


HGQo-021
SIZES, mils
6,000 psi body close to RE
CP-2
CP-1
CP
CP+1
CP+2
Mid region (32~38 in.) far from
4,000 psi
6,000 psi
12,000 psi w/o shim o-015
mid region @ 6,000 psi
Distance from RE, in.

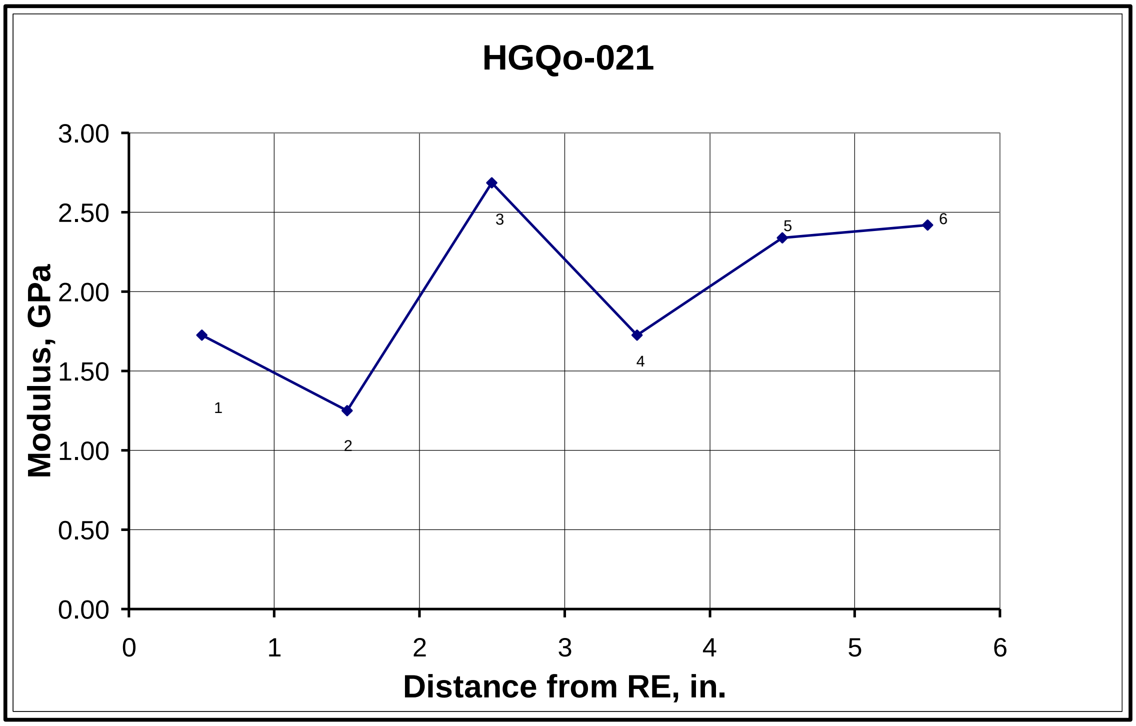


Fig. 4: *Outer Test Coil Size and Modulus*

The one-inch pusher block was applied carefully to the middle of the straight section and some certain length on the body closer to the ends, to compare the size of the ends to the straight section. It can be seen very clearly that the position # 2 is quite low compared to straight section. Therefore position # 2 is not only undersized but also soft. The same phenomenon was also seen on HGQ-03 coils. So extra effort was given to shim the ends to compensate for these low points. The shim plan will be discussed in a further section. Both of the test coils survived the end compression tests without damage.

4.4 Voltage Taps and Spot Heaters

The same layout used for HGQ-03 was used for HGQ-04 voltage tap installation. Voltage taps were mounted according to the drawing 5520-MD-344883 for inner coils and 5520-MD-344884 (rev. A) for outer coils.

The same technique used for early magnets to install the taps was used for HGQ-04 coils. The end compression tests with a 5 inch pusher block at 12000 PSI was conducted on coils with voltage taps already mounted to check for turn to turn shorts. One of the outer coils showed a turn to turn short at RE between the second and the third turn. Some attempt was done to locate the short location and to fix it. The effort was stopped to gain time and the spare test outer coil was used. (HGQo-23 was replaced with HGQo-21)

Two spot heaters, one in the splice region and the other one at the parting plane were mounted on two inner coils. Two more spot heaters, one each at the parting plane were also mounted on outer coils. The configuration of the parting plane spot heaters for both the inner and outer coils were slightly modified to fit the reduced length end saddles. The connection legs were moved to one side of the heater element instead of at opposite ends, as on HGQ03.
The change was only geometric and it did not affect the electrical properties of the heater.

5.0 Coil Assembly

5.1 Preload Adjustments: Magnet Body

The target coil prestress for both inner and outer coils in HGQ-04 was 83 MPa or12000 PSI. This prestress was designed to be obtained with an azimuthal coil size for inner coils +375 µm or 15 mil and +250 µm or 10 mil over the nominal size.
The outer coils were near the target size so no shimming was needed for the straight section of the outer coils. The inner coil sizes despite the increased insulation thickness and the curing cavity size were still under the desired goal. It was decided to put extra 3 mil Kapton shim at the parting plane of the inner coils from the end saddle on the LE to the end saddle on the RE.
The coil placement and shim sizes are shown in next figure:

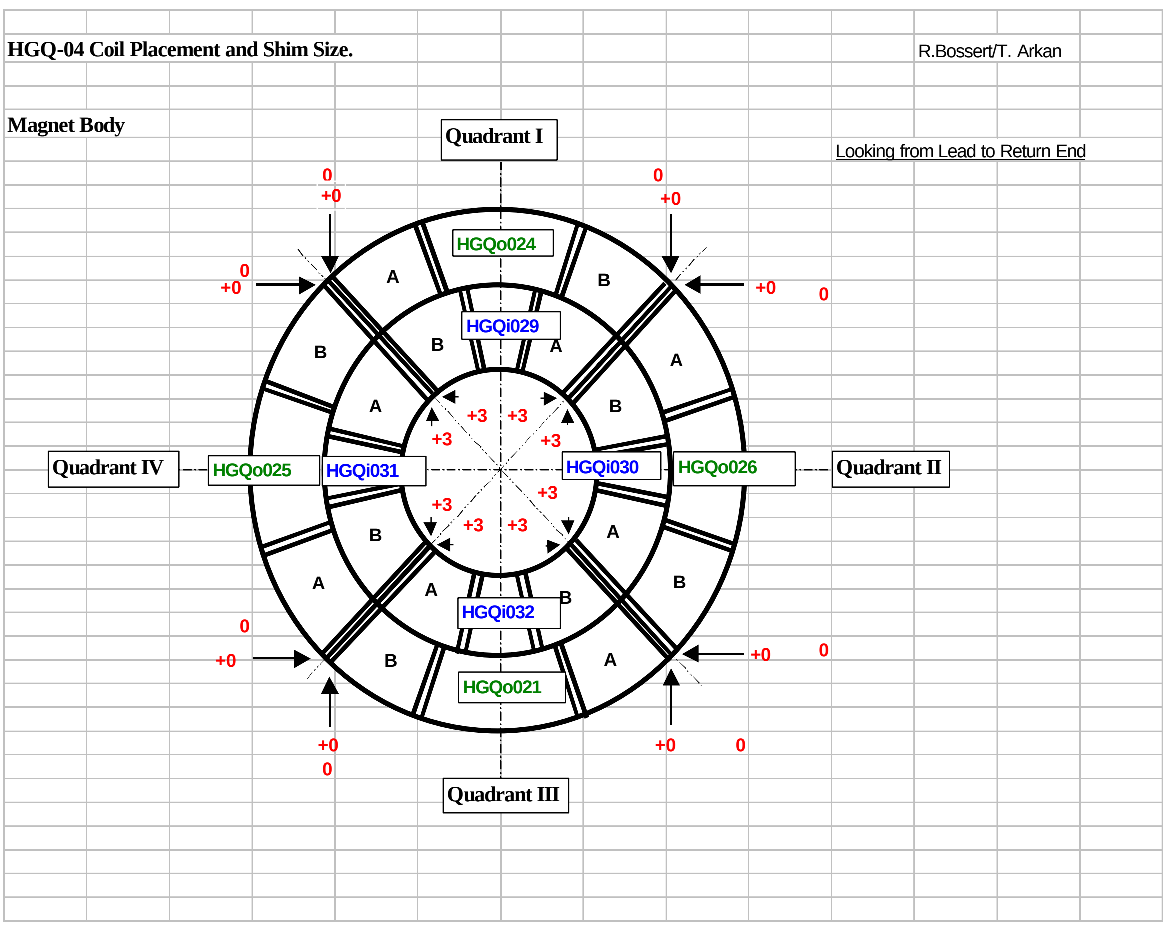


Fig. 5: *The coil placement and shimming for the Magnet body*

5.2 Preload Adjustments: Magnet Ends

From the end compression experiments conducted during the HGQ-03 production and HGQ-04 test coils, it can be seen the shape of the coils ends is very similar to each other. The result of the end-compression tests conducted for inner and outer test coils was a guideline for the end shimming of HGQ-04 coils. Taking into account that the same behavior of the ends were seen for HGQ-04 coils as other Ultem end coils, the same technique used for HGQ-03 coils was applied with some minor optimization to HGQ-04 coil ends. Fuji film tests were performed to check the accuracy of the HGQ-03 end-shimming plan. Test coils were shimmed and end compression tests were done with one and 5-inch pusher blocks and Fuji film readings were taken. After the investigation and study of the results, some optimization was done on shimming plan. The results after shimming showed that there is a gradual, uniform decrease in the size from the body on the coil to the end-saddle with the exception there is a big drop at the large current block (second measurement from the end-saddle of LE and RE).
Based on the discussions at the analysis meeting, a preliminary shimming plan was formulated. It is decided that shim plan has to take into account the cool down losses, Kapton deformation and the end parts deformities. The preliminary shim plan was as follow:

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- The end-saddles are 21-mm (0.827-in.) shorter than HGQ-03 for both inner and outer coils
- The cut for outer coils does not make a difference other than the total decrease in length
- The cut for inner coils caused a half hole notch which will create stress concentration during end-compression
- The Ultem 2300 used for end parts for HGQ-04 magnet coils are softer than the ones used for HGQ-02 and 03. The light brown Ultem used for HGQ-04 has 5 GPa tension modulus. The dark green Ultem used for HGQ-02 and 03 has 6.5 GPa tension modulus.

<u>Inner Coil:</u>

- HGQ-04 coils are 12 mil average. Body shim used for HGQ-03 will be reduced from 5 mil to 3 mil
- Cool Down losses compensation will be the same
- Kapton deformation compensation
- The depth at the ends will be shimmed as HGQ-03
- Radial shim will be measured and applied as needed, to bring coil areas in the ends to the same radial thickness as the end parts

Test coil (Inner # 28) will be squeezed at 4,000 and 6,000 PSI with 1-in. pusher block due to the softness of the light brown Ultem 2300 and the stress concentration created by the hole at the end of the saddle. Fuji film will be used.

<u>Outer Coil:</u>

- Cool Down losses compensation will be the same

- Kapton deformation compensation
- The depth at the ends will be shimmed as HGQ-03
- Radial shim will be measured and applied

Test coil (Outer # 21) will be squeezed at 4,000 and 6,000 PSI with 1-in. pusher block due to the softness of the light brown Ultem 2300. Fuji film will be used.

Fuji Film Test

Inner and outer test coil will be squeezed together with a Fuji film to monitor the stress distribution in inner-outer coil pair

If the shimming plan is OK, all real coils will be shimmed same way and will be squeezed with the 5-in. pusher block at 12,000 PSI to check for turn-to-turn shorts. Fuji film will be used.

To get more information on this shim plan technique and experiments conducted please refer to the HGQ-03 production report (section 5.2, TD-98-052)

The final shim plan used to shim the HGQ-04 coils is presented in the Appendix.

5.3 Ground Insulation and Strip Heaters

The ground insulation scheme was same the as HGQ-02 and HGQ-03. Strip heaters were placed between the inner and outer layer and between the outer layer and the collars. Standard strip heaters were placed between inner and outer coils. SSC type heaters (24 inches copper - 26 inches stainless steel - 24 inches copper) were used between outer coils and the collars. Stainless steel section of the heaters was centered on the straight section of the outer coils. To mount the outer coil SSC strip heaters, a layer of 125 µM Kapton insulation was removed leaving a 40 mil lip to compensate for the short width of SSC heaters compared to LBNL optimized copper coated heaters supplied by Al McInturff and used in HGQ-03.
The ground wrap insulation at LE and RE was carefully mounted to prevent any potential short for heater to collar ground short.

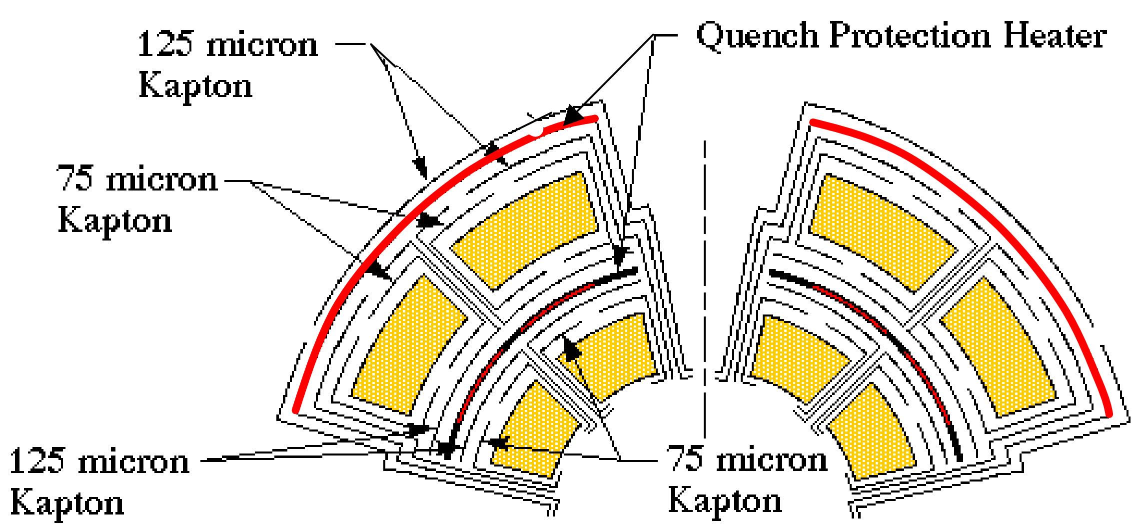


Fig. 6: *Ground insulation scheme and the strip heater locations.*

5.2 Key Extensions

Ultem key extensions which are 9.8 mm (3/8 in) long are placed at the back of the Ultem keys on both lead and return ends. These extensions fill the pole space of both inner and outer layers near the transition otherwise filled by the collar laminations. On the lead end of the magnet unmodified pole inserts were mounted whereas on the return end, pole inserts were modified to fill the spaces between the collars and the Ultem keys because of different coil lengths. A good drawing depicting this is given in the HGQ-02 production report, TD-98-019.
HGQ-02 key extensions taken out from the dismantled magnet were used in HGQ-04 with minor thickness modification at the RE for both inner and outer coils. Each gap between the inner and outer coil at RE was measured precisely and the key extension lip was machined according to these measurements. HGQ-03 and HGQ-02 key extensions were not shimmed azimuthally at the pole, but HGQ-04 key extensions were shimmed at pole for modulus difference of Ultem. The shim thickness for inner pole is 4 mil each side, 8 mil total and for outer pole is 10 mil each side total 20 mil.

6.0 Collaring and Keying

6.1 Collaring: Magnet Body

HGQ-04 magnet body was collared and keyed for the entire length of the straight section. Standard collar laminations are stacked in the straight section. The laminations were alternated to eliminate the twist in the collared coil assembly. This method works fine for dipole magnets. It is decided to be tried in quadropoles too. Over the last 3 inches, longitudinally, from LE and RE, a new application of collar lamination was used. Welded collar lamination packs were prepared. They were assembled as shown in drawing MD-369187. A fixture was designed to put the collars together during welding. The modifications were done at the machine shop and the packs were welded. The new two collar packs were mounted to the ends of the straight section. The locations for strain gauge collar laminations were determined based on the coil size data. The locations at which the coil size is lowest and highest was chosen so as to obtain the variation in the coil prestress. It can be seen clearly from Figure 2 that the inner coil size stays uniform through out length of the magnet in all the four coils. However, outer coils show gradual drop in size from LE to the middle of the magnet. Hence position #10 which the middle of the magnet and position #18 closer to RE were chosen for strain gauge locations as position #10 has the lowest coil size and position #18 has the largest coil size.
Two inner beam gauges, two outer beam gauges and two capacitor gauges are placed at each location. Each location also has two temperature-compensating gauges. The gauge placements at each location are shown below:

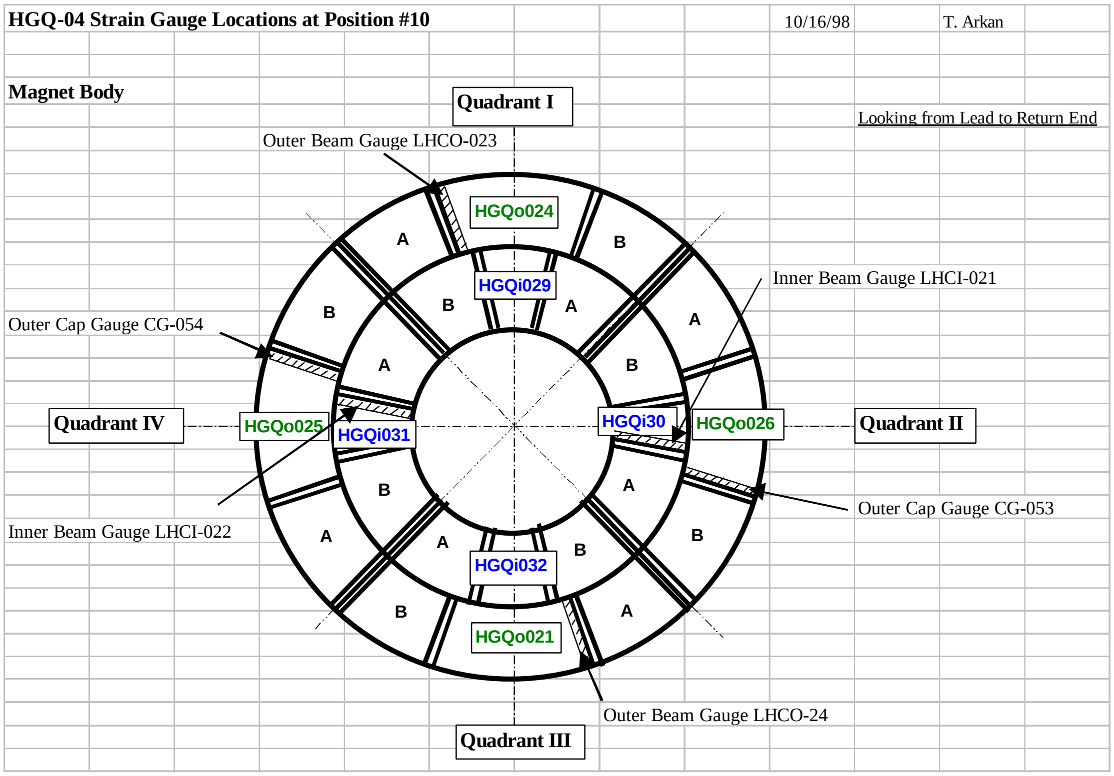


Fig. 7: *Magnet cross-section at Position #10 showing the Strain Gauge Locations.*

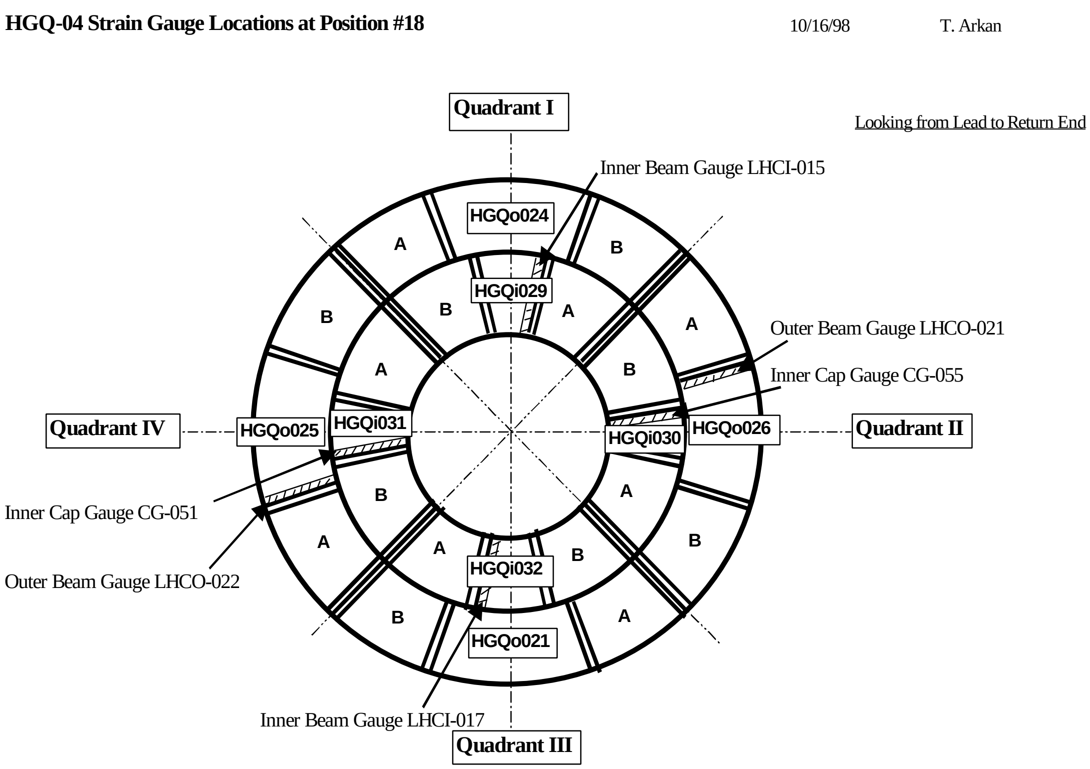


Fig. 8: *Magnet cross-section at Position #18 showing the Strain Gauge Locations.*

6. 2 Keying: The Magnet Body

The vertical keying procedure similar to that used for HGQ-03 was used to key the magnet body. Once the straight section was stacked with standard collar laminations, the magnet body was massaged at 1500 and 3000 pump PSI. The usual procedure was to key the middle of the magnet first and go from there to the ends. However, the tooling eventually to be used for the long production magnets will require the magnet to be keyed beginning from RE and proceeding to the LE. So, to test this procedure, HGQ04 was keyed in this manner. “Toggling”, or repeatedly alternating between main and key press pressure, was not used on HGQ04.

First, an attempt was made to fully key the magnet in one step. The first 3-inch pack to be keyed was the strain gauge pack at position #18 (near the RE). The 3-inch long collar section became deformed and buckled during this process. It was then decided not to fully key in one step, but use a two step procedure. First, the entire straight section was partially keyed, using 4500 main pusher pump PSI and 1500 key pusher pump PSI. Then the final key insertion took place in a second pass, using 6500 main pusher pump PSI and 3000 key pusher pump PSI.

Due to the response time lag of the pusher hydraulic system, after fully keying of the body, it was observed that 2 opposite quadrants keys were not completely seated into to their positions compared with the other two. The collared coil assembly was rotated 90 degrees inside the keying press. The 6500 main pusher pump PSI, and the 3000 keying press pump PSI was used to drive these keys in the rest of the way. After several iterations a fully keyed collared coil assembly was achieved. This new procedure is called two-step keying, and it was very successful. The collar slope and deflection of the 3 inches packs were definitely better that in the earlier collared coil assemblies. It is advised to use this two-step method for further magnets.

Before collaring with the welded new collar packs, the pole splices needed to be made. Areas to be spliced were preformed (filled with solder before the coil is wound) and then joined using the splice fixture. A cooling fixture was attached at the coil side so that the coil is not excessively heated. The length of the internal splice was about 114 mm, approximately equal to the cable transposition pitch.

Once the splices were done, and the key extensions were mounted, welded collar packs were mounted to RE and LE, and they were keyed the same way as the rest of the straight section.

The final prestress values in the magnet are given in Table 8. All the gauges are in the body of the magnet. The beam and cap gauges are placed at opposite poles, so in theory they should read the same preload. Further, the beam gauges and the cap gauges are placed in the same quadrant such that similar preloads should be measured.

The trend of the high value reading of the strain gauges in HGQ-03 continued in HGQ-04. From the force balance study conducted in HGQ-03 production report and from collar coil deflection data, one can say that these high prestress values read by strain gauges do not reflect reality. Further investigation and study of the gauges have to be completed to understand this behavior.

Gauge position and number	Coil pre-stress after "springback". Keys alone support coils.	
Position #10	PSI	MPa
Inner beam gauge, I-21	25614	177
Inner beam gauge, I-22	25280	174
Outer beam gauge, o-23	5871	41
Outer beam gauge, o-24	8055	55
Outer cap gauge, CG-53	12661	87
Outer cap gauge, CG-54	11963	83
Position #18		
Inner beam gauge, I-15	16614	114
Inner beam gauge, I-17	17845	123
Outer beam gauge, o-21	24484	169
Outer beam gauge, o-22	28907	199
Inner cap gauge, CG-51	14227	98
Inner cap gauge, CG-55	14665	101

Table 8: *Coil pre-stress values after keying*

6. 3 Installing the Aluminum End-Cans: Magnet Ends

HGQ-04 magnet ends were pre-stressed with an aluminum end-collet. HGQ-04 is the first internal splice magnet where both LE and RE had end-collets. A LE collet was reduced by half in length to fit the RE. After the keying of the magnet straight section was completed, the collared coil assembly was mounted on the end-clamping fixture. Fuji film was placed between the G-10 spacers and the coils for each quadrant both at RE and LE. The RE end-collet was first put on and from the Fuji film results, it was seen that the key extensions were misplaced and moved out of the magnet bore by ¾ of a millimeter. So obviously, the pressure mark of the key extension is more definite than the key itself and the conductors. After the can was completely installed, the Pi tape measurements were done and 12-mil deflection was measured on the diameter. The design required having 15-mil deflection to apply 83 MPa azimuthal and 28 MPa radial pressure to coil ends. So an extra 5 mil Kapton sheet was added under the G-10 spacers for each quadrant. The RE end-collet was installed and the end-ring, which prevents the slippage of the can out of the coils, was installed. On the other hand, for the LE, Fuji film showed that the key extension problem existed too and another problem was seen that the grooves cut out from the G-10 spacers to route the instrumentation wires out left an uncompressed region on the LE. After the further investigation of the Fuji film, it was seen that insufficient preload was applied to the splice region, due to the grooves. The grooves were filled with green putty with the routed wires so that enough preload was applied to this critical splice region. This caused the risk of losing some ramp splice voltage taps but they survived during the installation of the LE collet. The LE end-collet was installed with extra force. The existing fixture can apply 67,000 lbs. to drive the can on the coils. An extra 20,000-lbs. force was added with pancake cylinders to put the can on at the LE.

After the can was successfully installed, the Pi tape measurements were taken and 15-mil deflection was achieved for LE as RE. The LE end-can slipped off from the coils when the pressure of the fixture was removed, so to prevent this, the end-ring was tack welded to the end-can while the pressure was still on at the fixture during the installing of the LE can.

6. 4 Collared-Coil Deflection Measurements

The outer diameter of the collared-coil assembly was measured without the mandrel. The measurements were made both at the mid-plane region and pole region. Since the gauge readings show very high pre-stress in the coils, the OD measurements will confirm or reject the strain gauge readings.

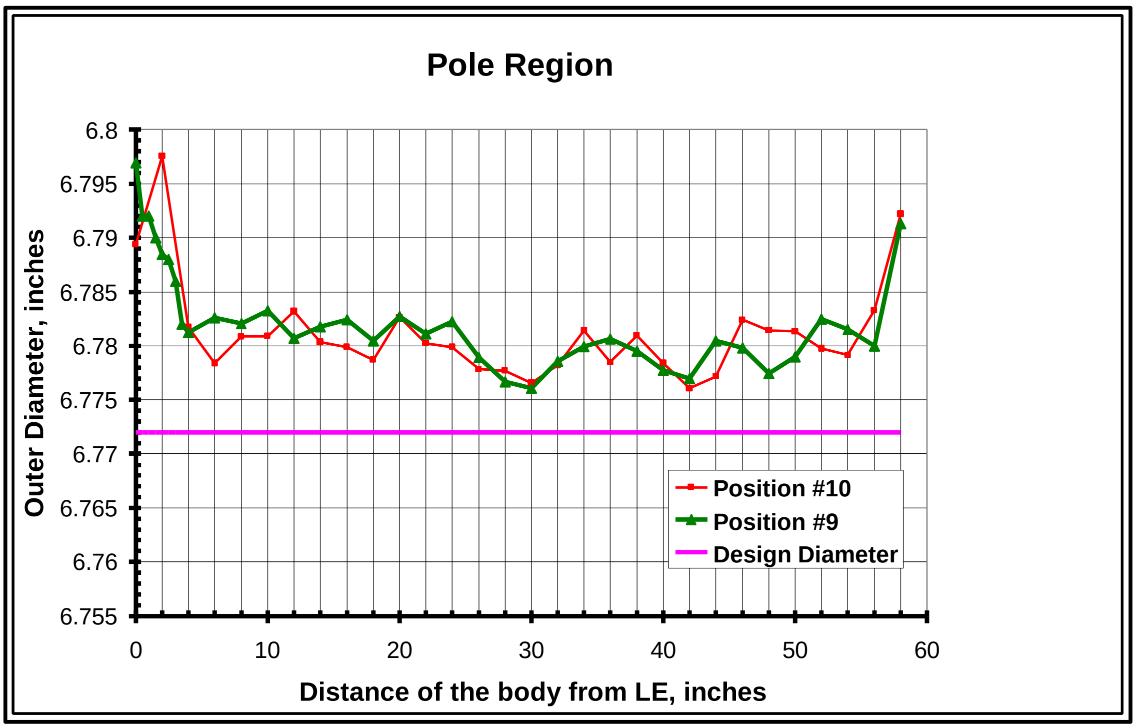


Fig. 9: *Deflection measurements at the pole region at two different positions, no mandrel*

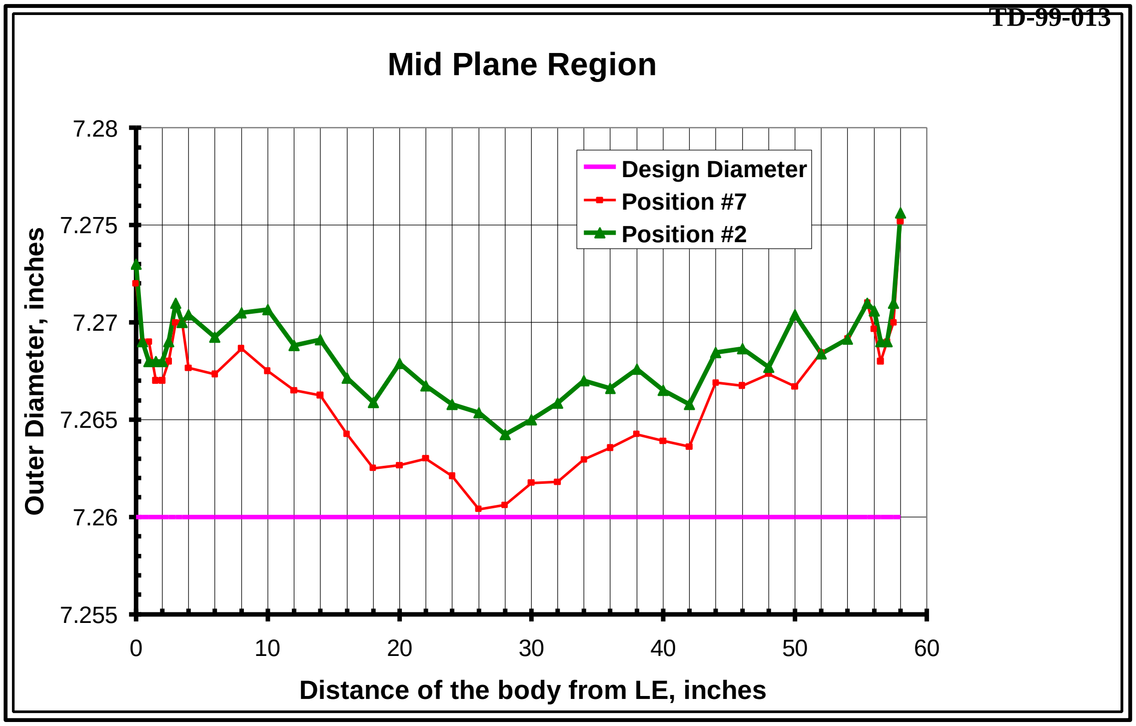


Fig. 10: *Deflection measurements at the mid-plane at two different positions, no mandrel*

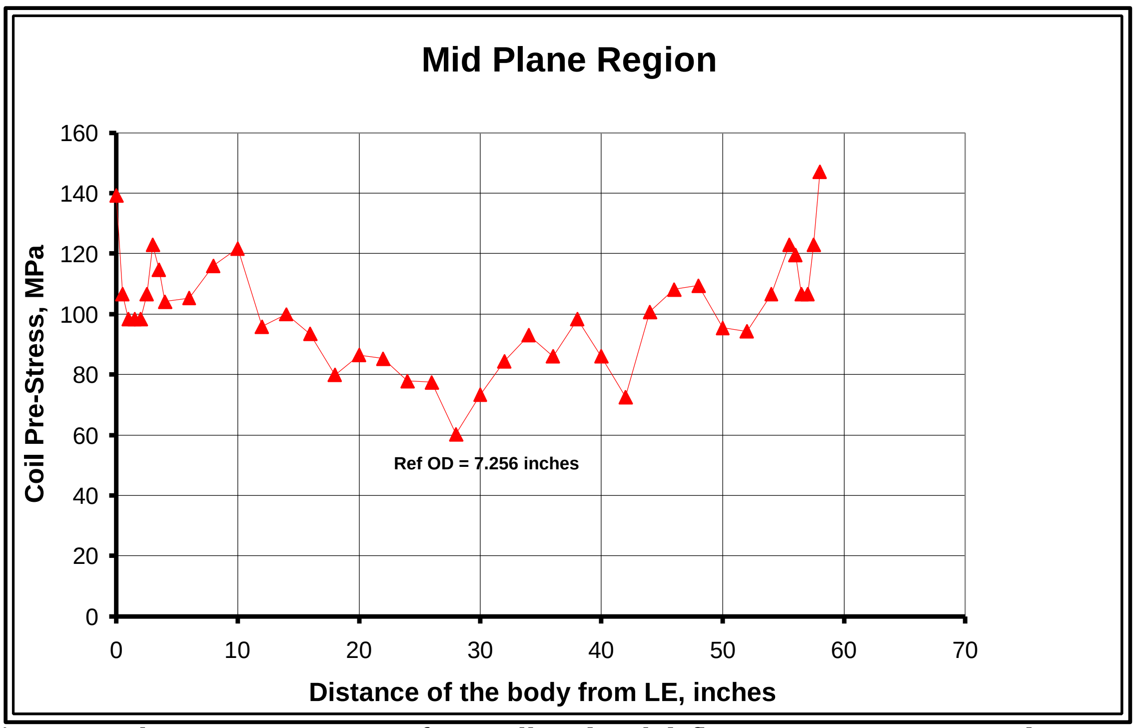


Fig. 11: *Coil pre-stress estimates from collared coil deflection measurements and FEA*

Even though the strain-gauge readings show very high coil pre-stress data, the collared-coil deflection measurements in the magnet body are quite normal and the magnitude of the deflection is similar to that of in HGQ-03. FEA computations (TD-97-051, TD-97-004 and TD-97-009; via JimK) suggests that for standard collar laminations, there is 1.55 ? m/MPa deflection on the radius. Using this value one can estimate the coil pre-stress using the collared coil deflection measurements. Fig. 11 shows these estimates and the average coil-prestress is around 90 MPa whereas beam gauge measurements showed very high prestress values. However outer and inner cap gauge measurements showed 80-100 MPa. Note that the reference OD by design is 7.26 inches but QC reports show that the collar laminations are off by 2 mils on radius and hence the OD for pre-stress estimates was considered to be 7.256 inches.

6. 5 Twist Measurements of the Collared-Coil Assembly

Twist in the collared-coil assembly was a problem for HGQ-02 and HGQ-03 production. HGQ-04 aimed not to have twist in collared-coil assembly. The keying procedure was changed from single step to two-step partially and fully keying of the collars. The collars were alternated to eliminate the twist. The method worked fine for dipoles.
Twist measurements was taking using the height gauge after placing the collared coil on a flat granite table. Fig 12 shows these measurements. The corresponding twist in milliradians is shown in Fig 13. One can see the amount of the twist of the straight section for the collared coil assembly is almost same at HGQ-03 and HGQ-04. So the taken precautions did not eliminate the twist. Further analysis is necessary for HGQ-05.

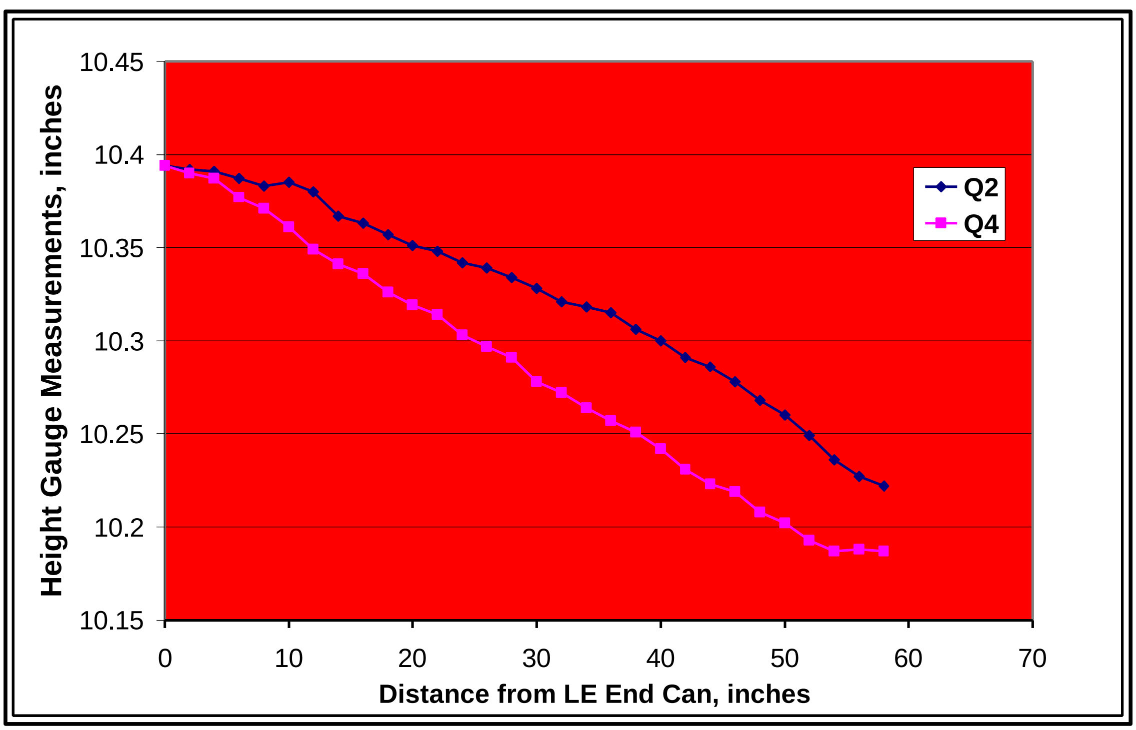


Fig. 12: *Height Gauge Measurements on the collared coil assembly*

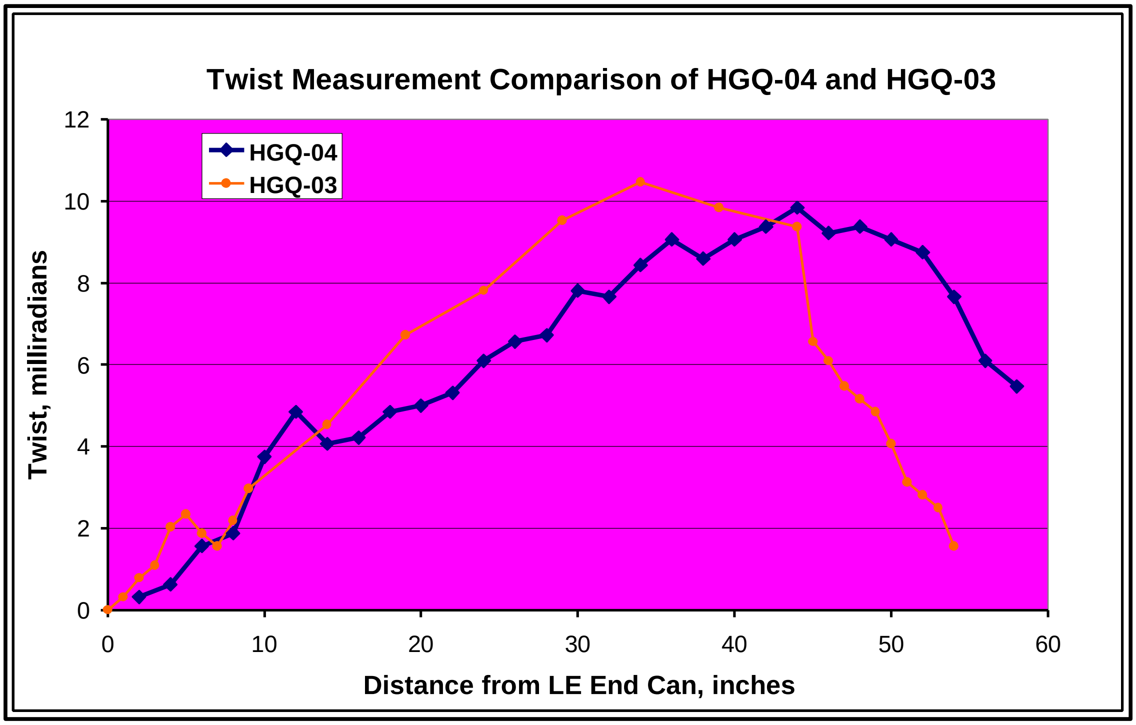


Fig. 13: *Comparison of the twist in the collared coil assembly straight section of HGQ-03 and HGQ-04 from height gauge measurements*

7. 0 Further Critical Issues

7. 1 Attachment of the End-Clamps to End-Plates

Longitudinal pre-loading of HGQ-02 and HGQ-03A was done with bullet loads. HGQ-03A collared coil assembly was locked to yoke laminations by adding shim along the axial magnet body. HGQ-04 was designed and the end cans were modified to have a longitudinal pre-loading achieved by a combination of bullets and attachment of the end-cans to end plate. Longitudinal thermal contraction was aimed to be eliminated by attaching end clamps to end plates. Calculations were made to prevent the slippage of the end can out of the end of the coils during cool down.
The safety factor on the return end can pullout was about 3:1 warm, which might cause one to make the hand-waving argument that the cold safety factor was about 2:1. The kapton-kapton coefficient of friction, .16 was chosen with a conservative approach.
Radial pressure of 28Mpa was used during calculations.
Calculated pullout force was:

(Area of contact)(coefficient of friction)(pressure) = pullout force.

(5.287in. Dia)(pi)(5.376in.long)(.16) (4060psi) = 58000 lb. warm, a safety factor of 2.9 warm over the 20000 lb. estimated force from longitudinal contractions during cooldown.

The experimental measured coefficient of friction of Kapton on Kapton is.36 for dynamic friction and .46 for static friction.
So the calculation now is:

(5.287in. Dia)(pi)(5.376in.long)(.36) (4000 PSI) = 128000 lb. warm, for a warm safety factor of 6.4.

The “collet pulloff force” was later tested. A fixture, using hydraulic cylinders, was positioned longitudinally between the lead and return end collet-clamps. Longitudinal force was applied between the clamps in such a way that it would cause the clamps to be pulled off the ends of the magnet. Forces as high as 18000 lbs. were applied. At 18000-lbs. force, the collared coil assembly stretched by .010 inches, but the end clamps did not move with respect to the coils.
Because the production of HGQ-04 was stopped, the end clamping technique was never tried. It is decided that the same technique will be used for HGQ-05.

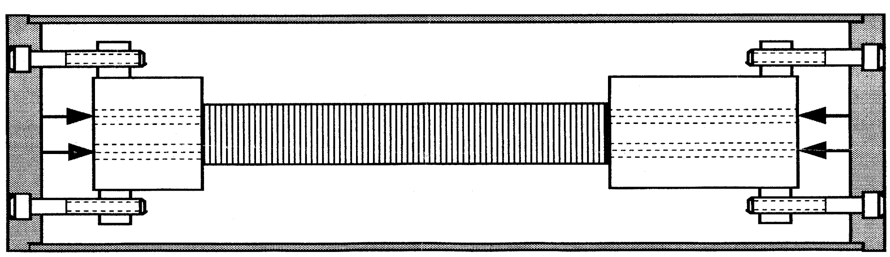
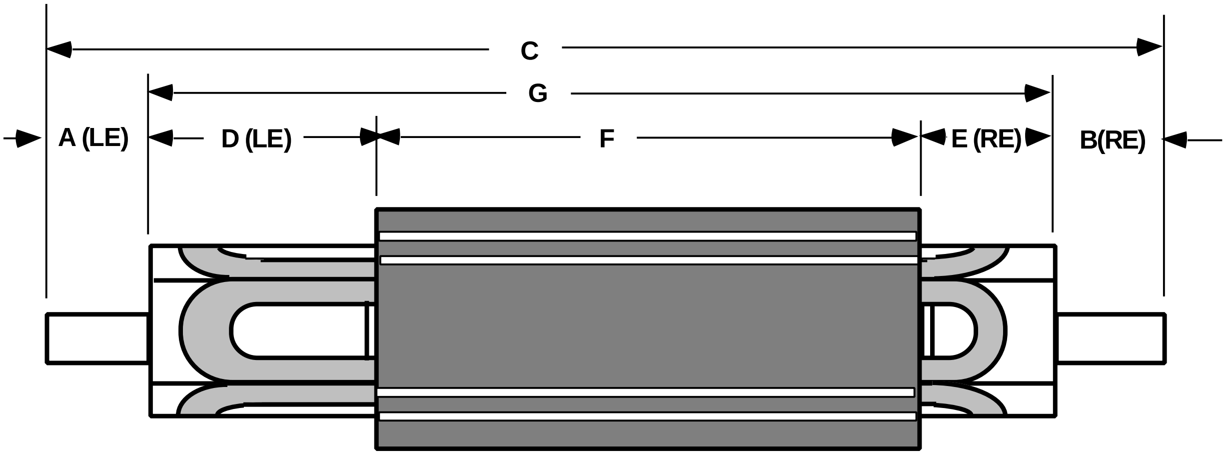


Fig. 14: *HGQ-04 End-Loading Mechanism*

Appendix - I: Dimensions after and before Collaring-Keying of HGQ-04

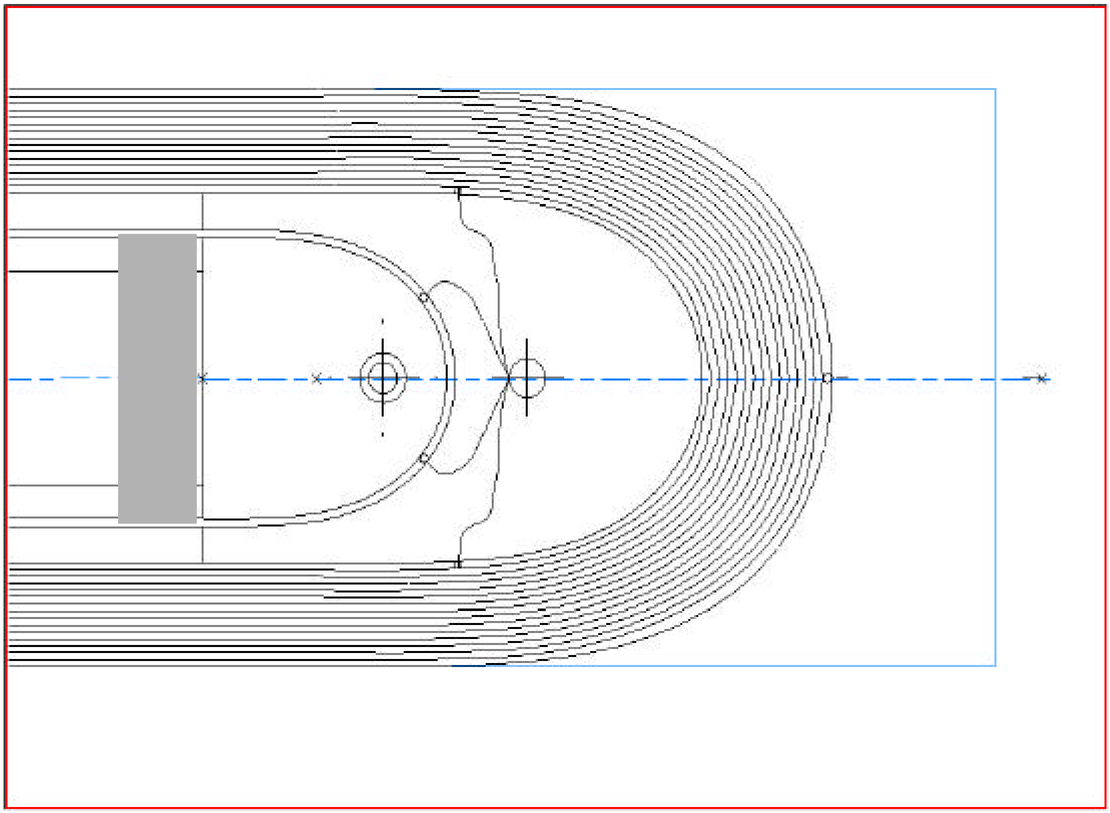


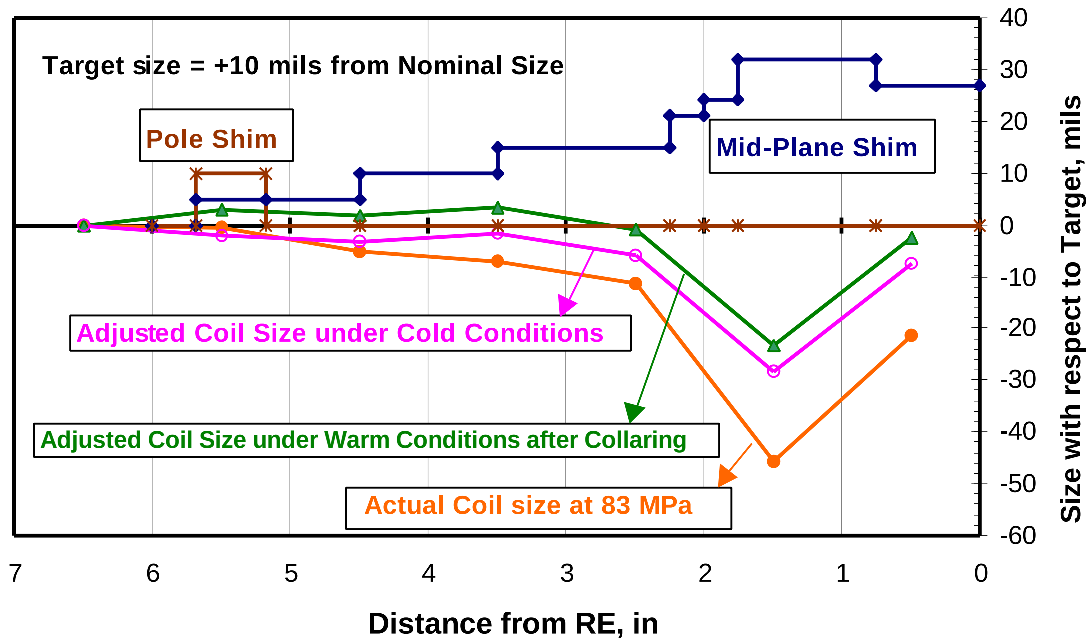
1	**On Mandrel Before Collaring**									
1'	**On Mandel After Collaring Before Keying**									
2	**On Mandrel After Collaring and Keying**									
3	**After Fully Keyed and Mandrel Pulled Out**									
G (Total Coil Length)										
	Q1	Q2	Q3	Q4			Q1	Q2	Q3	Q4
1	74.849	74.929	74.9945	74.938		delta (2-1)	0.057	0.0535	0.032	0.0545
2	74.906	74.9825	75.0265	74.9925		delta (3-2)	0.013	0.0005	-0.0445	-0.0195
3	74.919	74.983	74.982	74.973		delta (3-1)	0.07	0.054	-0.0125	0.035
D (LE)										
	Q1	Q2	Q3	Q4			Q1	Q2	Q3	Q4
1	10.975	11.026	11.033	11.013		delta (2-1)	0.019	0.0445	0.0345	0.0115
2	10.994	11.0705	11.0675	11.0245		delta (3-2)	-0.003	0.0045	0.0035	0.0175
3	10.991	11.075	11.071	11.042		delta (3-1)	0.016	0.049	0.038	0.029
E (RE)										
	Q1	Q2	Q3	Q4			Q1	Q2	Q3	Q4
1	5.524	5.615	5.585	5.574		delta (2-1)	0.0875	-0.001	0.042	0.056
2	5.6115	5.614	5.627	5.63		delta (3-2)	0.0035	0.018	0.005	-0.004
3	5.615	5.632	5.632	5.626		delta (3-1)	0.091	0.017	0.047	0.052
F (Collared Body Length)										
	Q1	Q2	Q3	Q4			Q1	Q2	Q3	Q4
1	58.375	58.33	58.4	58.36		delta (1'-1)	0.0185	-0.077	-0.1355	-0.107
1'	58.3935	58.253	58.2645	58.253		delta (2-1')	-0.1115	0.019	0.009	0.0345
2	58.282	58.272	58.2735	58.2875		delta (3-2)	0.0085	-0.0175	0.007	-0.0045
3	58.2905	58.2545	58.2805	58.283		delta (3-1')	-0.103	0.0015	0.016	0.03

1	**On Mandrel Before Collaring**									
2	**On Mandrel After Collaring and Keying**									
A (LE) Inner coil										
	Q1	Q2	Q3	Q4			Q1	Q2	Q3	Q4
1	10.229	10.205	10.217	10.228		delta (2-1)	0.074	0.062	0.043	0.055
2	10.303	10.267	10.26	10.283						
A (LE) Outer coil										
	Q1	Q2	Q3	Q4			Q1	Q2	Q3	Q4
1	10.238	10.187	10.176	10.189		delta (2-1)	0.06	0.041	0.051	0.071
2	10.298	10.228	10.227	10.26						
B (RE) Inner coil										
	Q1	Q2	Q3	Q4			Q1	Q2	Q3	Q4
1	4.908	4.9165	4.9035	4.901		delta (2-1)	-0.094	-0.102	-0.1005	-0.093
2	4.814	4.8145	4.803	4.808						
B (RE) Outer coil										
	Q1	Q2	Q3	Q4			Q1	Q2	Q3	Q4
1	4.8965	4.8955	4.891	4.888		delta (2-1)	-0.091	-0.0865	-0.091	-0.088
2	4.8055	4.809	4.8	4.8						

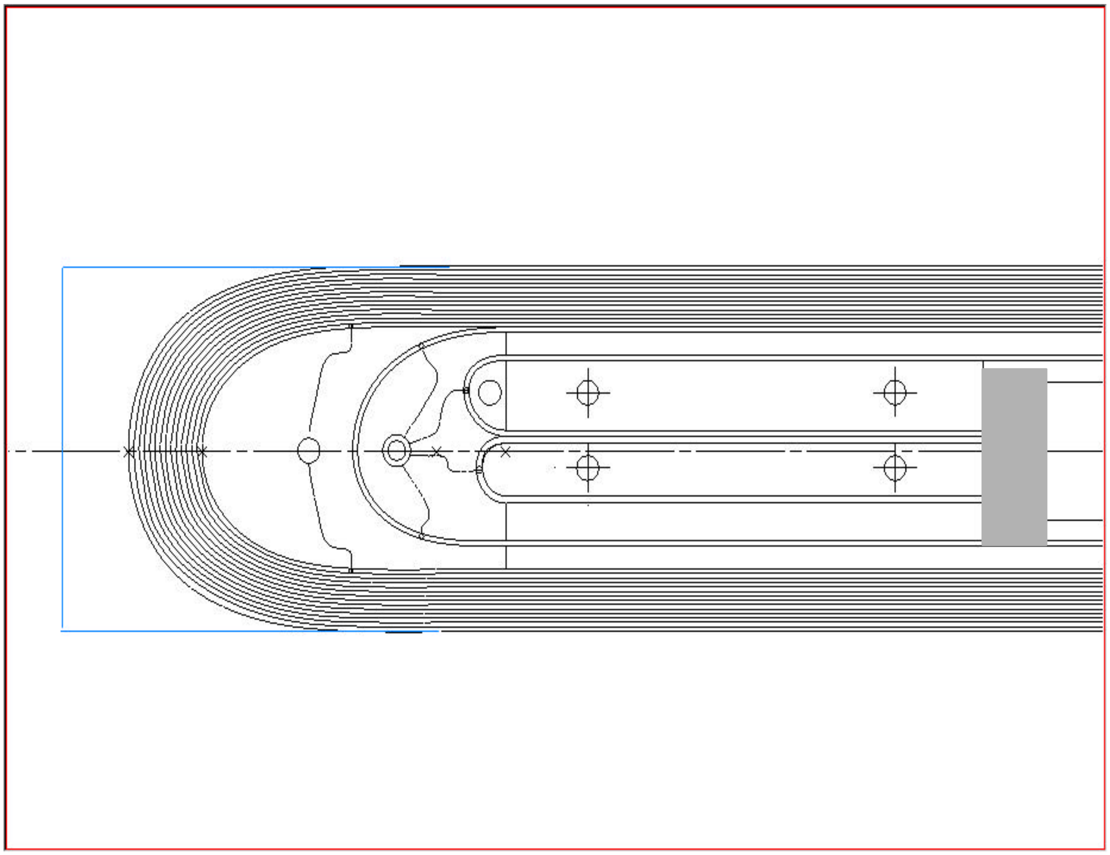
Appendix - II: End-Shimming Study for HGQ-04
(D. Chichili / T. Arkan)

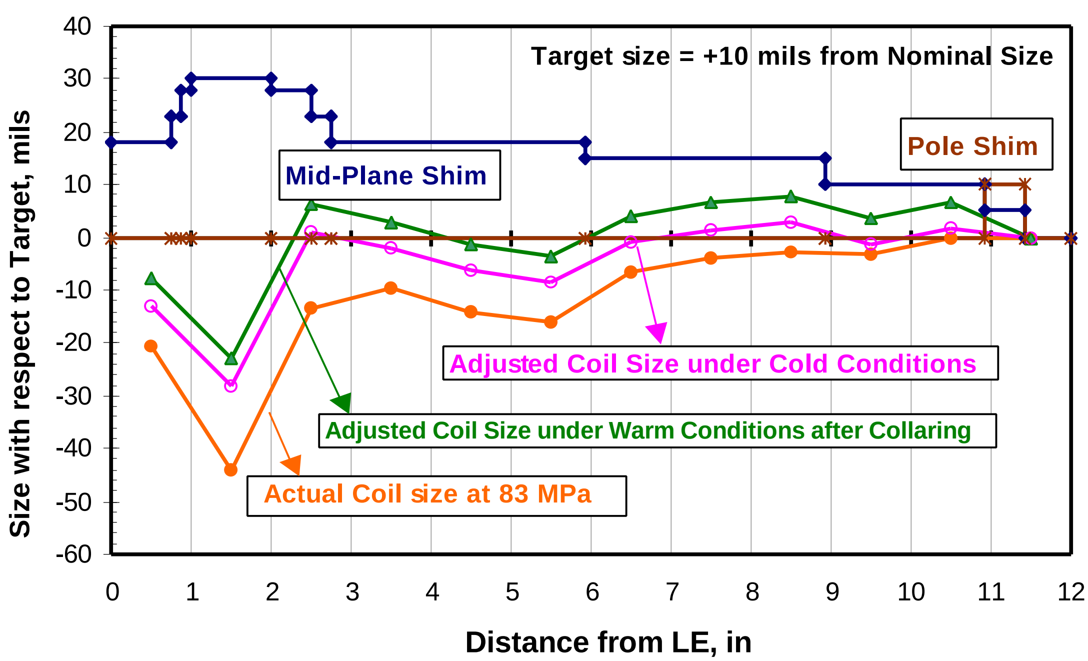
HGQ-04: OUTER RE



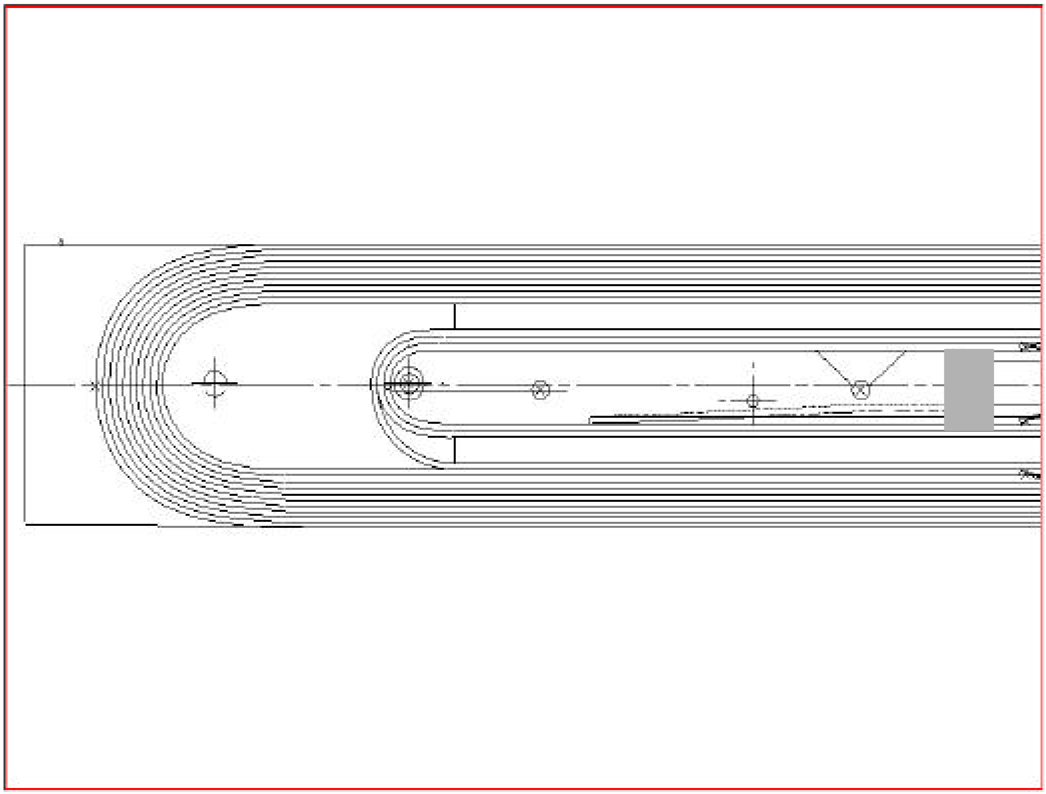


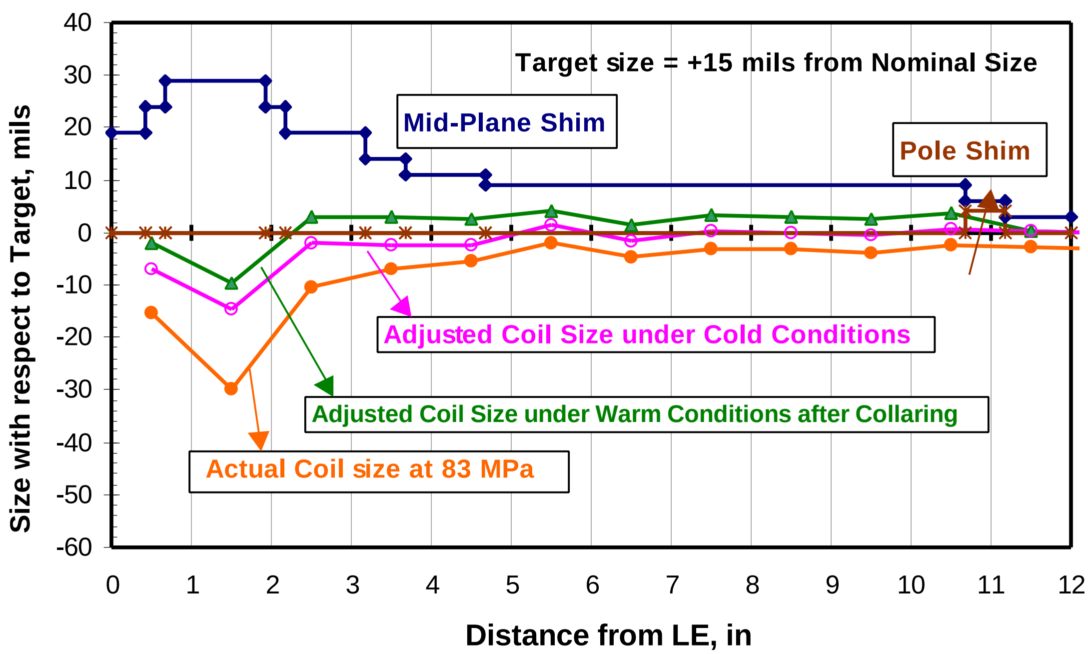
HGQ-04: OUTER LE





HGQ-04: INNER LE





HGQ-04: INNER RE